

---

# Natural Constants Determined to High Precision from Boltzmann's Constant and Avogadro's Number – A Challenge to Experiments and Astrophysical Observations to Match the Precision of the Results

---

[Dimitris M. Christodoulou](#)\*, [Demosthenes Kazanas](#), [Silas G. T. Laycock](#)

Posted Date: 15 September 2025

doi: 10.20944/preprints202509.0398.v2

Keywords: cosmology; coupling constants; fine-structure constant; gravitation; metrology; MOND theory; Planck system of units



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a Creative Commons CC BY 4.0 license, which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Article

# Natural Constants Determined to High Precision from Boltzmann's Constant and Avogadro's Number — A Challenge to Experiments and Astrophysical Observations to Match the Precision of the Results

Dimitris M. Christodoulou <sup>1,\*</sup>  Demosthenes Kazanas <sup>2</sup>  and Silas G. T. Laycock <sup>1</sup> 

<sup>1</sup> Lowell Center for Space Science and Technology, University of Massachusetts Lowell, Lowell, MA, 01854, USA

<sup>2</sup> NASA/GSFC, Astrophysics Science Division, Code 663, Greenbelt, MD 20771, USA

\* Correspondence: dimitris\_christodoulou@uml.edu or dchris32@depaul.edu

<sup>†</sup> Current address: Department of Mathematical Sciences, DePaul University, Chicago, IL 60614, USA.

## Abstract

In this investigation, we explore previously unknown relations between natural constants by taking the following steps: (1) We discard Dirac's constant  $\hbar$  from the universal man-made constants of physics, which we redefine in terms of Planck's constant  $h$ . (2) Working in the SI system of units, we determine Newton's gravitational constant  $G$  from Boltzmann's constant  $k_B$  and the elementary charge  $e$ , recognizing the entropy of matter as their common underlying characteristic. (3) By comparing the mass of 1 mole of electrons to the  $h$ -defined Planck mass  $M_P$ , we deduce nature's own molar constant ( $\approx 0.1$  mol) that contains a 'reduced Avogadro number'  $\mathfrak{N}_A = N_A/f_A$  of particles, where  $N_A$  is Avogadro's number and  $f_A \approx 10$  is the associated Avogadro factor. (4) From the new effective gravitational constant  $G_\star \equiv 4\pi\epsilon_0 G$ , where  $\epsilon_0$  is the vacuum permittivity, we obtain MOND's universal constant  $\mathcal{A}_0$  and its critical acceleration  $a_0$ , recognizing the Newtonian source of gravity as the common underlying characteristic and repudiating the need for a principle of equivalence of masses. (5) We derive the gravitational coupling constant  $\alpha_g$  solely from  $\mathfrak{N}_A$ . (6) We adopt the measured value of the  $h$ -defined fine-structure constant (FSC)  $\alpha$  and the value of  $\alpha_g$  (or, equivalently, nature's  $\mathfrak{N}_A$ ), and we determine the relative ratio  $\beta_g = \alpha_g/\alpha$  precise to 10 significant digits. (7) We derive the relative strong ratio  $\beta_s = \alpha_s/\alpha$  directly from the Avogadro factor  $f_A$ . (8) We determine the coupling constants of weak and strong interactions ( $\alpha_w$  and  $\alpha_s$ , respectively) in terms of the FSC  $\alpha$ . (9) The relation  $\alpha_w = \sqrt{\alpha}$  leads to a determination of the mass of the W boson  $m_W$  from the measured values of  $\alpha$  and the reduced Fermi constant  $G_F^0$ . (10) Using the Planck mass as a principal constant ( $M_P = \mathfrak{N}_A m_e$ , where  $m_e$  is the electron mass), we obtain new classical definitions of  $h$ ,  $\alpha$ , and the Compton radius  $r_C$ ; and we reformulate in a transparent, geometrically clear way several important QED equations, as well as the extended Planck system of units itself. We discuss the implications of these results, and we pave a way forward in exploring the unification of the fundamental forces of nature.

**Keywords:** cosmology; coupling constants; fine-structure constant; gravitation; metrology; MOND theory; Planck system of units

**MSC:** 81V10, 81V15, 81V17, 83C25, 85A04, 85A40

## 1. Introduction

In this work, we present a set of relations between fundamental physical constants across all scales and disciplines. We also correct and interrelate the dimensionless coupling constants of the four fundamental forces, and we reformulate the Planck system of units in a transparent way that provides straightforward interpretations of the quantities involved and their dependencies. These results could not have been obtained in the past; they emerge only now after correcting certain century-old conceptual

errors that have crept into the foundations of physics, distorting our man-made (subjective) definitions and our interpretations of the empirical force laws confirmed by experiments.

In the following two subsections, we describe these ingrained conceptual pitfalls and highlight the significant benefits arising directly from corrective actions (Sections 1.1 and 1.2, respectively). Section 1 wraps up with an outline of the remaining sections of the paper (Section 1.3).

### 1.1. Conceptual Pitfalls

#### 1.1.1. Dirac's Constant $\hbar$ , Our Inconspicuous Nemesis

In a scientific conference circa 1930, Paul Dirac proclaimed without explanation that the true universal constant was not Max Planck's  $h$  [1,2], but instead the 'reduced constant'  $\hbar = h/(2\pi)$  (see, e.g., [3,4]). No-one asked for an elaboration, the physicists in attendance must have thought that Dirac was conveniently simplifying the known equations of quantum mechanics by absorbing the  $2\pi$  into Planck's  $h$ , something that Erwin Schrödinger [5] also did at about the same time, calling the new constant  $K$ , but without any further assertion or declaration as to its physical significance.

But Dirac had a higher goal in mind than a mere simplification—and people went along with his idea for no counter-arguments were brought forth, until now. Sadly, by elevating  $\hbar$  to universal status, the  $2\pi$  imprint of two-dimensional (2-D) geometry, attached on to Planck's  $h$  for no good reason, disappeared from plain view forever. This miscue has since permeated the backbone of the physical sciences, causing gross misinterpretations of many fundamental constants featuring  $\hbar$ , a composite constant that always carries along an invisible tag of 2-D geometry [6].

Equations containing three-dimensional (3-D) geometric dependencies ( $4\pi$  terms), such as the fine-structure constant (FSC), lose their meaning due to odd combinations of disparate geometries; and pure 3-D equations, such as the Planck units, are erroneously imprinted with the unit of radian; although the presence of 2-D geometry cannot be detected since radians have been dropped from the SI unit of  $\hbar$  by international agreement.

Yet, certain facets of the problem were recently reported by Bunker et al. [7] who asked for radians to be reinstated in  $\hbar$ , and by Leblanc et al. [8] who showed that the Compton radius of the electron  $r_c = \hbar/(m_e c)$  (where  $m_e$  is the mass and  $c$  is the speed of light) is not a purely physical constant, since it oddly includes a geometric component. In contrast, there is no geometric imprint in the de Broglie wavelength  $\lambda = h/(m_e v)$  [9] of an electron moving at speed  $v$ ; all physical quantities are understood as being intrinsically three-dimensional, and no geometric term is needed to be included.

These important works did not succeed in exposing and clarifying the composite nature of  $\hbar$  in physics. The general perception is that using  $\hbar$  instead of  $h$  is beneficial, despite the fact that the additional justifications sought to strengthen this perception after the fact (e.g., [10]) can be patently rebutted and likely refuted.

#### 1.1.2. The Two Geometric Means of Two Natural Constants

It is well-known, though certainly underrated in the atomic world (the speed of light is not a unit in the atomic system of units [11]), that the vacuum establishes rules in its domain; these are the lower limits known as vacuum permittivity  $\epsilon_0$  and vacuum permeability  $\mu_0$ . In an impartial ("fair") vacuum that contemplates its properties equitably, the geometric-mean (G-M) relations of these properties should be present as well [6].

Thus, the unbiased combinations of  $\epsilon_0$  and  $\mu_0$  produce two ubiquitous thresholds known as the speed of light  $c$  (an upper limit by construction) and the impedance of free space  $Z_0$  (not a limit, just a threshold). From their G-M definitions, viz.

$$c = \sqrt{\epsilon_0^{-1} \mu_0^{-1}} \quad \text{and} \quad Z_0 = \sqrt{\epsilon_0^{-1} \mu_0}, \quad (1)$$

it seems that the vacuum establishes these four properties, and then it sits back, a mere observer of interactions between fields and particles that fill some of its space—which however must conform to the imposed rules.

On the other hand, certain details concerning the four vacuum constants are not at all clear. Specifically, (a) the speed of light is thought to be fundamental in nature although its G-M derivation indicates that  $c$  is simply a derivative; (b) whereas  $Z_0$  has never achieved the same recognition as  $c$ ; and (c) the fact that, besides  $c$ , the other three vacuum constants never appear in 3-D problems without an attached 3-D geometric factor of  $4\pi$  has gone unnoticed for more than a century.<sup>1</sup>

### 1.1.3. The Dimensional Constants of the Two Long-Range Force Fields

The appearance of the composite constant  $1/(4\pi\epsilon_0)$  in Coulomb's law has also gone unnoticed for more than a century, but it is a cause for concern. The problem is that the vacuum does not seem to impose the same constraint to Newton's gravitational law in which the normalizing constant  $G$  is not regulated by the vacuum and is not tagged by a 3-D geometric factor.

The obvious difference between these two fundamental laws should have rung a bell long ago. Instead, we teach our young to marvel at the amazing similarity between these two conservative long-range forces without paying attention to the attached constants. More than that, we have called "Coulomb's constant"  $K$  the  $1/(4\pi\epsilon_0)$  factor in Coulomb's law [12,13], burying the influence of the vacuum and achieving our hearts' desire, a "truly wonderful similarity" between the two conservative forces ( $F = GM_1M_2/r^2$  and  $F = KQ_1Q_2/r^2$ ). Talk about the wrong substitution!

Textbooks are silent on the principles of substitutions as applied to equations, inequalities, and expressions. The general consensus dictates that one can substitute any name for anything—after all, it is merely a renaming act. Here and in Section 1.1.1, we have demonstrated that substitutions lay out veils that conceal composite factors, and their compositions and internal properties may then be quickly forgotten.

### 1.1.4. The Centuries-Old Conundrum with Systems of Units

Physical insight has been repeatedly sacrificed in the name of convenience. Besides the SI system of units, all other systems have been created with the intention of setting various constants equal to 1 [14]. This common practice is predominantly useful in theoretical studies, which however are unable to produce actual numerical values, in which case researchers and authors back-pedal by restoring all units to their true forms. The SI system of units of measurement has become dominant precisely because it does not hide or suppress natural constants.

As will be seen below, setting the composite constant  $\hbar = 1$  has caused the largest losses in insightful physical interpretations, although historically the debates about setting  $\epsilon_0 = 1$  or  $4\pi\epsilon_0 = 1$  have also resulted in quite a few confusing arguments over many years [14,15].

### 1.1.5. The Man-Made Unit of 1 Mole and Avogadro's Number $N_A$

The SI unit of 1 mole has always played a central role in chemical measurements as well as in theoretical calculations [16], so much so that people are no longer concerned with its arbitrary character and the closely associated number of constituent particles expressed by Avogadro's number  $N_A$ . In the SI system,  $N_A$  is now taken to be 'exact' with 9 significant digits (SDs) [12,13].

These seemingly acceptable and internationally accepted definitions are not only arbitrary (like many other SI constants), but they also turn out to be the source of many problems in physical theory (unlike many other SI constants and like the definition of  $\hbar$ ). The reason for this unsuspected conundrum is that nature does not recognize or support the mole as one of her constants (unlike many other SI constants, such as speed  $c$ , charge  $e$ , and mass  $m_e$ ).

This damaging problem can only be resolved by finding nature's own 'molar unit' and the corresponding 'reduced Avogadro number' of particles (see Section 1.2.2 below).

### 1.1.6. Dimensionless Coupling Constants, a Century-Old Stumbling Block

Physical theory has defined four (man-made) coupling constants, one for each fundamental force of nature, and metrology has set out to measure experimentally three of them that are not negligibly small: the electromagnetic (EM) FSC  $\alpha$ , the weak coupling constant  $\alpha_w$ , and the strong

coupling constant  $\alpha_s$ . On the other hand, the gravitational coupling constant  $\alpha_g$  is calculated from other measured constants.

The current definitions of  $\alpha$  and  $\alpha_g$  are incorrect because Dirac's composite  $\hbar$  is used instead of Planck's purely physical 3-D constant  $h$ . Below, we define these two constants in terms of Planck's  $h$ , and the resulting adjusted values become clear and easy to interpret physically, thereby overturning numerous defeatist suppositions born of inadequate data in the published literature.

## 1.2. Significant Benefits

### 1.2.1. Understanding the Vacuum Constants $4\pi\epsilon_0$ , $\mu_0/(4\pi)$ , and $Z_0/(4\pi)$

Vacuum permittivity  $\epsilon_0$  and permeability  $\mu_0$  appear to be the two fundamental (minimum) constants introduced by the vacuum, although they are always imprinted by a factor of  $4\pi$ .<sup>2</sup> The G-M derivatives  $c$  and  $Z_0/(4\pi)$  are also introduced by the vacuum (Section 1.1.2). The factors of  $4\pi$  cancel out in the derivation of the speed of light, but not in the derivation of the impedance of free space, which then must always be considered in the form  $Z_0/(4\pi)$ . By construction, the speed of light describes a kinematic upper limit independent of the number of dimensions and valid in all possible directions.

The importance of the composite constant  $Z_0/(4\pi)$  cannot be understated. Not only does it always carry a factor of  $4\pi$ , but it also has a robust physical significance in 3-D space (just like the quantum of angular momentum  $\hbar$  does in 2-D space). A simple calculation shows that

$$\frac{Z_0}{4\pi} = \mathcal{R}_P, \quad (2)$$

where  $\mathcal{R}_P \equiv K/c$  is the unit of electric resistance in the Planck system [20] and  $K \equiv 1/(4\pi\epsilon_0)$  is Coulomb's constant.

Thus, we can describe self-consistently a set of six vacuum constants that are infused to matter, energy, particles, and fields when they materialize in the vacuum:

$$\text{Universal vacuum constants} := \left\{ \epsilon_0, \mu_0, 4\pi\epsilon_0, \frac{\mu_0}{4\pi}, \frac{Z_0}{4\pi}, c \right\}. \quad (3)$$

We have included  $\epsilon_0$  and  $\mu_0$  in this set because these terms appear to regulate alone the sources of EM fields, where formal geometric constraints require the  $2\pi$  or  $4\pi$  terms to be produced by line or volume integrations, respectively (Ampère's law [21], Gauss's law [22], and Maxwell's equations [23,24]).

### 1.2.2. Discovering Nature's Own Molar Unit and Its Number of Particles $\aleph_A$

The SI unit of 1 mole encapsulates the number and the cumulative mass of a group of like particles for which individual particle masses are measured experimentally. Unfortunately, this unit is arbitrary, and we can be certain that nature does not subscribe to it. This fact is responsible for our inability to connect certain fundamental constants, although some progress has been made recently (Ref. [6] and this work). Probably the only way of resolving such issues is to relate the unit of 1 mole and Avogadro's number  $N_A$  to physical constants that do not depend on our subjective choices, such as the ( $h$ -defined) units of the Planck system and the ( $h$ -defined) dimensionless constants that have not been included in any system of units [2,20,25–28].

In the following sections, we carry out such comparisons between units that have not been heretofore possible because of the erroneous use of Dirac's  $\hbar$  in 3-D physical settings. This exercise yields immediate benefits:

- The reduced Avogadro number  $\aleph_A$  corresponding to nature's molar unit is determined in two different ways.
- The gravitational coupling constant  $\alpha_g$  is determined solely in terms of  $\aleph_A$ , a long-sought hypothesized connection.

- (c) The Planck mass  $M_P$  is directly proportional to the electron mass  $m_e$ , a feat previously thought to be unfeasible [25].
- (d) Several universal constants are found to be derivatives, thereby resolving the conundrum concerning which constants are truly fundamental in nature [25–28].
- (e) The Planck system of units [2,20] is reformulated in simple and clear terms with distinct composite constants (Section 1.2.4) describing static and moving charges (electric currents).

### 1.2.3. Relating the Coupling Constants of the Four Fundamental Forces

The ratio of Avogadro's number  $N_A$  to the reduced value  $\aleph_A$  is a new universal constant that we call the Avogadro factor  $f_A$ . Its value is  $f_A \approx 10$ , so nature's own molar unit is about 0.1 mol. This determination is obtained from  $\alpha_g$  or from  $M_P$  and, independently, from the relative strong coupling ratio  $\beta_s = \alpha_s/\alpha$ ; and yields relations between the coupling constants of the four fundamental forces. Below we express these constants in terms of the ( $h$ -defined) FSC which is currently known to a precision of 11 SDs from its inverse ( $\alpha^{-1} \approx 861$ ; Ref. [6]) measured to 12 SDs ([29]; PDG Refs. [30,31]; CODATA Refs. [12,13]).

### 1.2.4. Defining Two Convenient Vacuum-Tagged Effective Gravitational Constants $G_\star$ and $G_B$

In a surprising series of derivations:

- (1) The SI numerical value of Newton's gravitational constant  $G$  is found to be a derivative of the constants  $e$  (elementary charge),  $4\pi\epsilon_0$  (vacuum permittivity), and  $k_B$  (Boltzmann's constant). This shows that  $G$  carries information about the entropy of the gravitational field.
- (2) We define two effective gravitational constants imprinted by vacuum EM constants, viz.

$$G_\star \equiv (4\pi\epsilon_0)G, \quad (4)$$

and

$$G_B \equiv \left(\frac{\mu_0}{4\pi}\right)G. \quad (5)$$

They indicate that the vacuum coupled to  $G$  may act on gravitational fields as well as on EM and QED fields, a property that becomes evident in the reformulated Planck system of units.

- (3) Constant  $G_B$  signifies the presence of moving charges and electric currents.
- (4) Constant  $G_\star$  scales the source of the gravitational field  $G_\star M$  produced by an inertial mass  $M$  and dispenses with the need for an equivalence principle of masses [32].
- (5) The strength (numerical value) of  $G_\star$  naturally scales the source of gravity in MOND as well. In particular,

$$\mathcal{N}(\mathcal{A}_0) = \mathcal{N}(G_\star), \quad (6)$$

where  $\mathcal{A}_0$  is MOND's universal constant [33,34] and the numerical function  $\mathcal{N}(\cdot)$  indicates that units are set aside. Furthermore,  $\mathcal{N}(a_0) = \mathcal{N}(4\pi\epsilon_0)$ , where  $a_0$  is MOND's critical acceleration. These relations indicate that the constants of MOND do not have a cosmological origin. The MOND constants are discussed in detail in Appendix A.

- (6) Important QED constants (such as Planck's  $h$ , the Compton radius  $r_c$ , and the FSC  $\alpha$ ) are found to have a classical origin (perhaps even a 'gravitational' origin). They are all expressed in terms of the composite constant  $G(\aleph_A)^2$ , but they assume their simplest forms when written in terms of the classical Planck mass  $M_P = \aleph_A m_e$ .

### 1.2.5. Understanding the Stoney Mass $M_S$ and Length $L_S$

The Stoney units of mass and length [28] are obtained easily from the two G-Ms of the constants  $e^2$  and  $G_\star$ . This reasoning that uses G-Ms is relatively recent, but it has led to new, previously undetected physical relations (Refs. [6,35,36] and this work).

The Stoney mass  $M_S$  is discussed in detail in Appendix B. It shows that the source term of the gravitational field  $G_\star M_S \propto k_B$ , whereas the electron's gravitational source term  $G_\star m_e \propto k_B/\aleph_A$ .

The Stoney length  $L_S$  has not been previously appreciated despite exhibiting two important properties: (a)  $L_S \equiv R_e$ , where  $R_e$  is the charge radius of the electron [37,38], a length scale that also appears in Reissner-Nordström black-hole physics [39–46]; and (b)  $\mathcal{N}(L_S) = \mathcal{N}(k_B) \times 10^{-13}$ , indicating that entropy information encoded into  $G_\star$  is passed on to a linear setting with just one degree of freedom.

Constants  $G_\star$  and  $G_B$  ( $\propto G_\star$ ) introduce entropy considerations into the EM section of the Planck system of units, whereas Newton's  $G$  (also  $\propto G_\star$ ) is the carrier of such information in the mechanical section of the reformulated system. Details are given in Section 5 below.

### 1.2.6. Discovering the Weak Interaction and a New Natural Charge $Q_\star$

The ratio of charge  $e$  to the Planck charge  $Q_P$  produces the weak coupling constant  $\alpha_w \approx 0.034$ . This result may be surprising, although the individual constants are well-known. In our formulation that uses the  $h$ -defined FSC, such a relation was expected because experimental measurements show clearly that  $\alpha_w = \sqrt{\alpha}$ .

On the other hand, the G-M of the two charges yields a brand-new charge scale, viz.

$$Q_\star = \sqrt{e Q_P}. \quad (7)$$

The three charges form the geometric sequence  $\{e, Q_\star, Q_P\}$  with common ratio

$$\frac{Q_P}{Q_\star} = \frac{Q_\star}{e} = \alpha_w^{-1/2} \approx 5.4169. \quad (8)$$

Besides the appearance of  $\alpha_w$  as an electroweak constant, the significance (if any) of the  $Q_\star$  scale is currently not understood.

### 1.3. Outline

The remainder of the paper is organized as follows:

- In Section 2, we present in tabular form the calculations that demonstrate numerous relations and dependencies between various universal constants.
- In Section 3, we present the calculations that determine various quantum mechanical constants from other classical constants.
- In Section 4, we analyze the geometric imprints in various proposed QED equations in which Dirac's  $\hbar$  has been used routinely.
- In Section 5, we present the reformulated Planck system in a simple and concise form based on our choice of 7 fundamental (field+vacuum+molar) constants, i.e.,  $\{e, m_e, k_B; \epsilon_0, \mu_0; N_A, f_A\}$ .
- In Section 6, we discuss briefly our results and summarize our conclusions.
- In Appendix A, we summarize additional information concerning MOND's universal constant  $\mathcal{A}_0$  [33,34], its critical acceleration  $a_0$ , and the source term  $\mathcal{A}_0 M$  of the gravitational field due to a mass  $M$ .
- In Appendix B, we discuss the G-M of  $e^2$  and  $G_\star^{-1}$  known as the Stoney mass [28], and the source term  $G_\star m_e$  of the gravitational field of the electron.
- In Appendix C, we provide summary tables in which we collect and categorize all the relations between constants and units discussed in this paper.

## 2. Relations Involving Universal Constants

We explore relations between well-known universal constants. We derive only one new constant, the Avogadro factor  $f_A$  that scales Avogadro's number  $N_A$  to the reduced natural value  $\mathfrak{N}_A = N_A/f_A$ . The value of  $f_A \approx 10$  is determined in two different ways (from the Planck mass and the strong coupling constant) which dispels notions of a mere coincidence.

The results are presented in tabular form, and they are summarized in the 11 tables that follow. Each table lists the measured input parameters at the top and the derived constants at the bottom. The results are separated from the input parameters by a horizontal line in each table. Notes below each table report on the details of the measurements and the calculations.

Most of the results (including Newton's  $G$ , nature's  $\aleph_A$ , and Planck's  $M_P$ ) are given to a precision of at least 10 SDs. Only the mass of the  $W$  boson is reported to 7 SDs because the input reduced Fermi constant  $G_F^0$  is currently measured to 8 SDs [13,31].

### 2.1. Table 1

Table 1 shows the initial discovery that  $\mathcal{N}(k_{B,\text{MeV}}) = \mathcal{N}(\sqrt{G_\star})$ . The entropy constant  $k_{B,\text{MeV}}$  is Boltzmann's constant measured in MeV. The elementary charge  $e$  does not appear because of the chosen units (but see Table 2 for an alternative calculation using different units).

### 2.2. Table 2

Table 2 shows the calculation of Newton's  $G$  from  $G_\star$  which was obtained from the more precise Boltzmann's constant and the elementary charge using different sets of units. The numerical calculations of the results are carried out by the formulae shown in the 'Source' column. The full equations are obtained by equating each listed 'Symbol' to its 'Source,' e.g.,  $\mathcal{N}(G_\star) = \mathcal{N}(k_{B,\text{MJ}}/e)^2$  and  $G = G_\star/(4\pi\epsilon_0)$ . The value of  $G$  is determined to a precision of 10 SDs and is compared to experimental results in the notes to the table.

### 2.3. Table 3

Table 3 shows the calculations of the Planck units of mass, length, and charge using their standard definitions, but with Planck's constant  $h$  restored in place of  $\hbar$ . These numerical values differ from those quoted in the literature by factors of  $\sqrt{2\pi} \approx 2.5$ .

### 2.4. Table 4

Table 4 shows the calculations of the Avogadro factor  $f_A$  and the reduced Avogadro number  $\aleph_A$  for which  $\aleph_A$  electrons have a cumulative mass equal to the Planck mass determined in terms of Planck's  $h$  (that is,  $\aleph_A m_e = M_P$ , where  $M_P = \sqrt{\hbar c/G}$ ). The derived natural values of  $f_A$  and  $\aleph_A$  are not arbitrary; they also determine the relative strong coupling constant  $\beta_s = \alpha_s/\alpha$  and the gravitational coupling constant  $\alpha_g = Gm_e^2/(\hbar c)$ , respectively.

### 2.5. Table 5

Table 5 establishes the identities  $\mathcal{N}(\mathcal{A}_0) = \mathcal{N}(G_\star)$  and  $\mathcal{N}(a_0) = \mathcal{N}(4\pi\epsilon_0)$  for the MOND constants  $\mathcal{A}_0$  and  $a_0$ , respectively. In retrospect, the magnitudes of  $\mathcal{A}_0$  and  $G_\star$  could not have been different because they both appear in the source of the gravitational field ( $G_\star M$  in Newtonian gravity and  $\mathcal{A}_0 M$  in MOND for a mass  $M$ ). Thus, the source of gravity has the same strength in the two regimes, although the MOND force is modified on the whole by a square root [49], an action that changes the units of  $\mathcal{A}_0$ .<sup>3</sup>

### 2.6. Table 6

Table 6 shows two determinations of the gravitational coupling constant  $\alpha_g$ . The conventional definition uses Planck's  $h$  (instead of  $\hbar$ ), but it no longer seems to be fundamental or have a QED origin since  $\alpha_g$  can now be tied directly to the reduced Avogadro number  $\aleph_A$ .

### 2.7. Table 7

Table 7 shows the calculation of the relative gravitational coupling ratio  $\beta_g \equiv \alpha_g/\alpha$ . We have chosen the FSC as the normalizing constant because it is measured to very high precision. Such relative ratios of dimensionless constants can be incorporated into systems of units in the same fashion as the dimensional units. The reference value of the  $h$ -defined  $\alpha^{-1} \approx 861$  [6] is also important in resolving the

long-standing scientific obsession with the  $\hbar$ -defined value of number 137 [53,54] which turns out to be irrelevant and unphysical.

### 2.8. Table 8

Table 8 shows the values of the weak, strong, and gravitational couplings when these constants are expressed in terms of the fundamental constants  $\mathfrak{N}_A, f_A$ , and the FSC. These results are new. Comparisons with experimental values, as well as several alternative representations, are given in the notes to the table. We note, in particular, the surprising relations  $\alpha_w = \sqrt{\alpha}$  and  $\alpha_w = e/Q_P$ .

### 2.9. Table 9

Table 9 shows the mass of the W boson calculated from the reduced Fermi constant and the FSC. This result is new. Comparisons with experimental values are given in the notes to the table. The calculated value differs from the latest high-precision CDF measurement [55] by only 0.163%.

### 2.10. Table 10

Table 10 shows the complete list of calculated relative coupling ratios  $\{\beta_w, \beta_s, \beta_g\}$ . These ratios are available to be included in any chosen system of units. We note, in particular, the fundamental relations  $\beta_s = (f_A)^2$  and  $\beta_w = 1/\sqrt{\alpha}$ . These relative coupling ratios are included automatically in any system of measurements with base units  $f_A, N_A$ , and  $\alpha$ .

### 2.11. Table 11

Table 11 summarizes the determinations of the Stoney units of mass and length [28] calculated from the two G-Ms of the constants  $e^2$  and  $G_*$ . The Stoney length  $L_S$  holds a surprise: the leading coefficient of its numerical value (1.380 649) is identical to that of Boltzmann's constant  $k_B$ , yielding an independent determination of this unit from the exact equality  $\mathcal{N}(L_S) = \mathcal{N}(k_B) \times 10^{-13}$ .

The factor of  $10^{-13}$  is composite, formed as the product of  $10^{-7}$  carried by  $\mu_0/(4\pi)$  and  $10^{-6}$  contained in the unit of  $k_{B,MJ}$  (last note in Table 11). This (sub)multiple may turn out to be common in unit conversions and numerical evaluations. As an example, consider the exact equality

$$\alpha_w = \frac{\mathcal{N}(F_P)}{\mathcal{N}(\Theta_P)} \times 10^{-13}, \quad (9)$$

where  $F_P = c^4/G$  and  $\Theta_P = M_P c^2/k_B$  are the Planck units of force and temperature, respectively, and  $\alpha_w = \sqrt{\alpha}$  in terms of the FSC. The origin of the factor of  $10^{-13}$  is not obvious, as there is no implicit dependence of the units on the magnetic permeability  $\mu_0/(4\pi)$ . The puzzle becomes easier to solve when one considers the relations  $\alpha_w = L_S/L_P$  and  $\mathcal{N}(L_S) \propto 10^{-7}$  presented in the notes to Table 11.

**Table 1.**  $\mathcal{N}(k_{B,MeV}) = \mathcal{N}(\sqrt{4\pi\epsilon_0 G})$ , a numerical identity rooted to entropy that shows nature imprinting the same property in different settings irrespective of units and their (sub)multiples.\*

Constant	Symbol	Value	SDs	SI Unit	Source
Vacuum Permittivity	$\epsilon_0$	$8.854\,187\,8188(14) \times 10^{-12}$	11	F m <sup>-1</sup>	CODATA
Gravitational Constant	$G$	$6.674\,30(15) \times 10^{-11}$	6	m <sup>3</sup> kg <sup>-1</sup> s <sup>-2</sup>	CODATA
Boltzmann Constant	$k_{B,MeV}$	$8.617\,333\,262 \times 10^{-11}$	Exact	MeV K <sup>-1</sup>	CODATA
G-M of $4\pi\epsilon_0$ and $G$	$\sqrt{4\pi\epsilon_0 G}$	$8.617\,5(1) \times 10^{-11}$ **	5	C kg <sup>-1</sup>	Calculated

\*The SI system of units and their derivatives are used throughout this analysis; all other systems of units suffer from inconsistencies introduced for the sake of simplicity (e.g.,  $G = 1$ ,  $c = 1$ ,  $4\pi\epsilon_0 = 1$ , and so on). \*\*We attribute the 19.35-ppm difference to the poorer measurements of  $G$ , and we use Boltzmann's constant to obtain a more precise value of  $G$  in Table 2 below.

**Table 2.** CODATA universal constants are used to determine to a high precision of 10 SDs the gravitational constants  $G_\star \equiv 4\pi\epsilon_0 G$  (effective) and  $G$  (Newtonian) shown at the bottom.

Constant	Symbol	Value	SDs	SI Unit	Source
Vacuum Permittivity	$\epsilon_0$	$8.854\ 187\ 8188(14) \times 10^{-12}$	11	F m <sup>-1</sup>	CODATA
Boltzmann Constant	$k_{B,MeV}$	$8.617\ 333\ 262 \times 10^{-11}$	Exact	MeV K <sup>-1</sup>	CODATA
	$(k_{B,MeV})^2$	$7.425\ 843\ 255 \times 10^{-21}$	Exact	MeV <sup>2</sup> K <sup>-2</sup>	Calculated
Elementary Charge	$e$	$1.602\ 176\ 634 \times 10^{-19}$	Exact	C	CODATA
Boltzmann Constant	$k_{B,MJ}$	$1.380\ 649 \times 10^{-29}$	Exact	MJ K <sup>-1</sup>	CODATA
	$(k_{B,MJ}/e)^2$	$7.425\ 843\ 255 \times 10^{-21}$	Exact	MJ <sup>2</sup> K <sup>-2</sup> C <sup>-2</sup>	Calculated
Effective Grav. Constant	$G_\star$	$7.425\ 843\ 255 \times 10^{-21}$	Exact*	C <sup>2</sup> kg <sup>-2</sup>	$\mathcal{N}(k_{B,MeV})^2$ or $\mathcal{N}(k_{B,MJ}/e)^2$
Gravitational Constant	$G$	$6.674\ 015\ 081(1) \times 10^{-11}$ **	10	m <sup>3</sup> kg <sup>-1</sup> s <sup>-2</sup>	$G_\star/(4\pi\epsilon_0)$

\*We adopt  $G_\star$  as exact since Boltzmann's constant and the elementary charge are exact in the SI system.

\*\*The 2018-2022 world average  $6.674\ 30(15) \times 10^{-11}$  m<sup>3</sup> kg<sup>-1</sup> s<sup>-2</sup> [12,13] matches the first 4 error-free SDs. The average of CODATA recommended values 1998-2022 matches 5 SDs. One of four recent high-precision experiments [47,48] also matched 5 SDs.

**Table 3.** CODATA universal constants and Newton's  $G$  from Table 2 are used to determine the original Planck units of mass  $M_P$ , length  $L_P$ , and charge  $Q_P$  shown at the bottom.\*

Constant	Symbol	Value	SDs	SI Unit	Source
Vacuum Permittivity	$\epsilon_0$	$8.854\ 187\ 8188 \times 10^{-12}$	11	F m <sup>-1</sup>	CODATA
Light Speed	$c$	$2.997\ 924\ 58 \times 10^8$	Exact	m s <sup>-1</sup>	CODATA
Planck Constant	$h$	$6.626\ 070\ 15 \times 10^{-34}$	Exact	J Hz <sup>-1</sup>	CODATA
Gravitational Constant	$G$	$6.674\ 015\ 081 \times 10^{-11}$	10	m <sup>3</sup> kg <sup>-1</sup> s <sup>-2</sup>	Table 2
Planck Mass	$M_P$	$5.455\ 628\ 310 \times 10^{-8}$	10	kg	$\sqrt{hc/G}$
Planck Length	$L_P$	$4.051\ 264\ 068 \times 10^{-35}$	10	m	$\sqrt{hG/c^3}$
Planck Charge**	$Q_P$	$4.701\ 296\ 730 \times 10^{-18}$	10	C	$\sqrt{4\pi\epsilon_0 hc}$

\*We emphasize that Planck's 3-D universal constant  $h$  is implemented in all man-made definitions instead of the erroneous 2-D constant  $\hbar$ , whereas  $\hbar$  is replaced by  $h/(2\pi)$  in all natural equations in which the presence of the  $2\pi$  is justified.

\*\*The Planck charge  $Q_P$  is intimately connected to the elementary charge  $e$  in various ways: (a) the G-M of  $e^2$  and  $(1/Q_P)^2$  is the weak coupling constant  $\alpha_w$ , leading to the relation  $\alpha_w = e/Q_P$  (Table 8); (b) the other G-M of  $e^2$  and  $Q_P^2$  with dimensions of [charge]<sup>2</sup> leads to the relation  $Q_\star^2 = e Q_P$ , so a new charge  $Q_\star$  is the G-M of  $e$  and  $Q_P$  and  $Q_\star = 8.678\ 886\ 893 \times 10^{-19}$  C; (c) the charges  $\{e, Q_\star, Q_P\}$  form a geometric progression with common ratio  $1/\sqrt{\alpha_w} \approx 5.4169$ . Furthermore, the following relations hold for these charges:  $Q_\star^2 = M_P \sqrt{e^2 G_\star}$  and  $Q_P = M_P \sqrt{G_\star}$ , which also imply the numerical identities  $\mathcal{N}(Q_\star)^2 = \mathcal{N}(M_P)\mathcal{N}(k_{B,MJ})$  and  $\mathcal{N}(Q_P) = \mathcal{N}(M_P)\mathcal{N}(k_{B,MeV})$ , respectively.

**Table 4.** CODATA universal constants and Planck mass  $M_P$  from Table 3 are used to determine the Avogadro factor  $f_A$  and the reduced Avogadro number  $\mathfrak{N}_A$  shown at the bottom.\* Then, an antithesis is formulated in the last row of the table: the fundamental constants  $\mathfrak{N}_A$  and  $m_e$  are used to define the Planck mass in a novel way.

Constant	Symbol	Value	SDs	SI Unit	Source
Avogadro Number	$N_A$	$6.022\ 140\ 76 \times 10^{23}$	Exact	—	CODATA
Electron Mass	$m_e$	$9.109\ 383\ 7139 \times 10^{-31}$	11	kg	CODATA
Mass of 1 mole of Electrons	$N_A m_e$	$5.485\ 799\ 0962 \times 10^{-7}$	11	kg	Calculated
Planck Mass	$M_P$	$5.455\ 628\ 310 \times 10^{-8}$	10	kg	Table 3
Avogadro Factor	$f_A$	10.0553 0213	Exact	—	$N_A m_e / M_P$
Inverse Avogadro Factor	$f_A^{-1}$	0.099 450 020 21	Exact	—	Calculated
Reduced Avogadro Number**	$\mathfrak{N}_A$	$5.989\ 020\ 203 \times 10^{22}$	Exact	—	$N_A / f_A$
Planck Mass (new definition)	$M_P$	$5.455\ 628\ 310 \times 10^{-8}$	10	kg	$\mathfrak{N}_A m_e$

\*We adopt the derived constants as exact to align with Avogadro's number  $N_A$  which is exact in the SI system.

\*\*The reduced Avogadro number determines the gravitational coupling constant ( $\alpha_g = 1/(\mathfrak{N}_A)^2$ , Table 6 below) and the Planck mass ( $M_P = \mathfrak{N}_A m_e$ ) which, in turn, determines many other universal constants (including  $h = GM_P^2/c$ ) and helps reformulate the Planck system of units in the simple form presented in Tables 12 and 13 below.

**Table 5.** The effective gravitational constant  $G_\star$  from Table 2 is used to determine the MOND constants shown at the bottom.\*

Constant	Symbol	Value	SDs	SI Unit	Source
Effective Grav. Constant	$G_\star$	$7.425\ 843\ 255 \times 10^{-21}$	Exact	$\text{C}^2 \text{kg}^{-2}$	Table 2
Vacuum Permittivity	$\epsilon_0$	$8.854\ 187\ 8188(14) \times 10^{-12}$	11	$\text{F m}^{-1}$	CODATA
MOND Universal Constant	$\mathcal{A}_0$	$7.425\ 843\ 255 \times 10^{-21}$	Exact	$\text{m}^4 \text{kg}^{-1} \text{s}^{-4}$	$\mathcal{N}(G_\star)$
MOND Critical Acceleration	$a_0$	$1.112\ 650\ 0562(18) \times 10^{-10}$	11	$\text{m s}^{-2}$	$\mathcal{N}(4\pi\epsilon_0)$

\*The identities  $\mathcal{N}(\mathcal{A}_0) = \mathcal{N}(G_\star)$  and  $\mathcal{N}(a_0) = \mathcal{N}(4\pi\epsilon_0)$  indicate that the MOND constants are determined by gravity and the vacuum; thus, they are not connected to cosmological constants as previously thought. Some of the conclusions obtained from these numerical equalities are discussed in Appendix A.

**Table 6.** Gravitational constant  $G$  from Table 2 and reduced Avogadro number  $\aleph_A$  from Table 4 are used to determine the gravitational coupling constant  $\alpha_g$  in two different ways\* shown at the bottom.

Constant	Symbol	Value	SDs	SI Unit	Source
Gravitational Constant	$G$	$6.674\ 015\ 081 \times 10^{-11}$	Exact	$\text{m}^3 \text{kg}^{-1} \text{s}^{-2}$	Table 2
Electron Mass	$m_e$	$9.109\ 383\ 7139 \times 10^{-31}$	11	kg	CODATA
Planck Constant	$h$	$6.626\ 070\ 15 \times 10^{-34}$	Exact	$\text{J Hz}^{-1}$	CODATA
Light Speed	$c$	$2.997\ 924\ 58 \times 10^8$	Exact	$\text{m s}^{-1}$	CODATA
Reduced Avogadro Number	$\aleph_A$	$5.989\ 020\ 203 \times 10^{22}$	Exact	—	Table 4
Grav. Coupling Constant	$\alpha_g$	$2.787\ 972\ 231 \times 10^{-46}$	10	—	$Gm_e^2/(hc)$
Grav. Coupling Constant	$\alpha_g$	$2.787\ 972\ 231 \times 10^{-46}$	Exact	—	$1/(\aleph_A)^2$

\*We have always thought that  $\alpha_g$  has a quantum mechanical origin because it utilizes Planck's  $h$ ; now, nature reveals that the fundamental definition of  $\alpha_g$  is the one involving the reduced Avogadro number which, in turn, reveals that the inverse Avogadro factor  $f_A^{-1} \approx 0.10$  (Table 4) is nature's molar unit: thus,  $f_A^{-1} \approx 0.10$  moles of electrons contain  $\aleph_A \approx 6.0 \times 10^{22}$  particles of total mass  $M_P \approx 5.5 \times 10^{-8}$  kg. As a result, a fair number of currently espoused ideas ought to be allowed to fade.<sup>4</sup>

**Table 7.** Gravitational coupling constant  $\alpha_g$  from Table 6 and inverse FSC are used to determine the relative coupling ratio  $\beta_g$  shown at the bottom.

Constant	Symbol	Value	SDs	SI Unit	Source
Grav. Coupling Constant	$\alpha_g$	$2.787\ 972\ 231 \times 10^{-46}$	Exact	—	Table 6
Inverse FSC	$\alpha^{-1}$	861.022 576 584	12	—	CODATA*
Inverse FSC	$\alpha^{-1}$	861.022 576 6	10	—	$G_\star(M_P/e)^2$
Relative Grav. Coupling Ratio	$\beta_g$	$2.400\ 507\ 034 \times 10^{-43}$	10	—	$\alpha_g/\alpha$

\*The  $\hbar$ -dependent CODATA value of  $\alpha^{-1} = 137.035\ 999\ 177(21)$  is multiplied by  $2\pi$  in accordance with our definition of  $\alpha \equiv Ke^2/(hc)$ .

**Table 8.** Inverse FSC from Table 7 and Avogadro constants from Table 4 are used to determine the fundamental coupling constants shown at the bottom. Copied from Table 6, constant  $\alpha_g$  completes the list of couplings.\*

Constant	Symbol	Value	SDs	SI Unit	Source
Inverse FSC	$\alpha^{-1}$	861.022 576 584	12	—	Table 7
Avogadro Factor	$f_A$	10.0553 0213	Exact	—	Table 4
Reduced Avogadro Number	$\aleph_A$	$5.989\ 020\ 203 \times 10^{22}$	Exact	—	Table 4
Fine-Structure Constant	$\alpha$	$1.161\ 409\ 7321 \times 10^{-3}$	11	—	$1/\alpha^{-1}$
Weak Coupling Constant	$\alpha_w$	$3.407\ 946\ 203 \times 10^{-2}$ **	10	—	$\sqrt{\alpha}$
Strong Coupling Constant	$\alpha_s$	$1.174\ 290\ 938 \times 10^{-1}$ ***	10	—	$(f_A)^2 \alpha$
Grav. Coupling Constant	$\alpha_g$	$2.787\ 972\ 231 \times 10^{-46}$	Exact	—	$1/(\aleph_A)^2$ , Table 6

\* Alternative relations involving  $M_P$ :  $\alpha_g = (m_e/M_P)^2$ ;  $\alpha = (M_S/M_P)^2$ , where  $M_S$  is the Stoney mass from Table 11;  $\alpha_w = M_S/M_P$ ;  $\alpha_s = (f_A M_S/M_P)^2$ . Also,  $G_\star = (Q_P/M_P)^2$  and  $\alpha_w = e/Q_P$ , where  $Q_P$  is the Planck charge from Table 3.

\*\*To be compared to the PDG [31] world average of  $3.3914(11) \times 10^{-2}$  and the latest CDF [55] value of  $3.3969(08) \times 10^{-2}$ .

\*\*\*To be compared to the PDG [31] world average of  $1.180(9) \times 10^{-1}$ .

**Table 9.** FSC and reduced Fermi constant are used to determine the mass of the W boson  $m_W$  shown at the bottom.

Constant	Symbol	Value	SDs	SI Unit	Source
Fine-Structure Constant	$\alpha$	$1.161\,409\,732\,1(2) \times 10^{-3}$	11	—	Table 8
Reduced Fermi Constant	$G_F^0$	$1.166\,378\,8(6) \times 10^{-5}$	8	(GeV) <sup>-2</sup>	PDG [31]
Mass of W boson	$m_W$	$80.5645\,5(2)^*$	7	(GeV)/c <sup>2</sup>	$(\pi/G_F^0)^{1/2}(\alpha/2)^{1/4}/c^2$

\* To be compared to the PDG [31] world average of 80.3692(133) and the latest CDF [55] value of 80.4335(94), both in the same units.

**Table 10.** Avogadro factor and FSC are used to determine the relative weak and strong coupling ratios  $\beta_w$  and  $\beta_s$  shown at the bottom. Copied from Table 7, constant  $\beta_g$  completes the list of relative couplings that are available for use in any chosen system of units.

Constant	Symbol	Value	SDs	SI Unit	Source
Avogadro Factor	$f_A$	10.0553 0213	Exact	—	Table 4
Fine-Structure Constant	$\alpha$	$1.161\,409\,7321 \times 10^{-3}$	11	—	Table 8
Relative Strong Coupling Ratio	$\beta_s$	101.109 1009 *	Exact	—	$(f_A)^2$
Relative Weak Coupling Ratio	$\beta_w$	29.343 186 20	10	—	$1/\sqrt{\alpha}$
Relative Grav. Coupling Ratio	$\beta_g$	$2.400\,507\,034 \times 10^{-43}$	10	—	$\alpha_g/\alpha$ , Table 7

\* To be compared to  $\alpha_s/\alpha = 101.6(8)$  from experiments, where the PDG [31] world average of  $\alpha_s$  is 0.1180(9).

**Table 11.** Stoney units of mass  $M_S$  and length  $L_S$ , where  $L_S$  also represents the electron's charge radius  $R_e$  that appears in black-hole physics. These units are effectively expressed by the two G-Ms of  $e^2$  and  $G_\star$ .\*

Constant	Symbol	Value	SDs	SI Unit	Source
Vacuum Permeability	$\mu_0$	$4\pi \times 10^{-7}$	10	N A <sup>-2</sup>	$1/(\epsilon_0 c^2)$
Elementary Charge**	$e$	$1.602\,176\,634 \times 10^{-19}$	Exact	C	CODATA
Effective Grav. Constant	$G_\star$	$7.425\,843\,255 \times 10^{-21}$	Exact	C <sup>2</sup> kg <sup>-2</sup>	Table 2
Stoney Mass	$M_S$	$1.859\,248\,778 \times 10^{-9}$	Exact	kg	$\sqrt{e^2(G_\star)^{-1}}$
Stoney Length	$L_S$ or $R_e$	$1.380\,649\,000 \times 10^{-36}$ ***	10	m	$(\frac{\mu_0}{4\pi})\sqrt{e^2 G_\star}$

\* These units can also be expressed in terms of Planck units and coupling constants:  $M_S = M_P \alpha_w$  and  $L_S = L_P \alpha_w$ , where  $\alpha_w = \sqrt{\alpha}$  as well.

\*\* Also adopted as the Stoney charge.

\*\*\* Since  $(\frac{\mu_0}{4\pi})$  introduces only a power of  $10^{-7}$  to the source, then  $N(L_S) = N(k_{B,M}) \times 10^{-7}$ .

**Table 12.** Mechanical Planck units reformulated in terms of the subset of units  $\{M_P, G, c, k_B\}$  of which only  $k_B$  is a fundamental constant.\*

Unit	Symbol	Planck Definition	Reformulation
Mass	$M_P$	$M_P = \sqrt{h c/G}$	$M_P = \aleph_A m_e$
Length	$L_P$	$L_P = \sqrt{h G/c^3}$	$L_P = M_P G/c^2$
Time	$T_P$	$T_P = \sqrt{h G/c^5}$	$T_P = M_P G/c^3$
Temperature	$\Theta_P$	$\Theta_P = \sqrt{h c^5/G}/k_B$	$\Theta_P = M_P c^2/k_B$
Force	$F_P$	$F_P = c^4/G$	$F_P = M_P c^2/L_P$
Pressure	$P_P$	$P_P = c^7/(h G^2)$	$P_P = M_P c^2/L_P^3$
Acceleration	$a_P$	$a_P = \sqrt{c^7/(h G)}$	$a_P = c^2/L_P$

\* Our RPS set of fundamental units includes field+vacuum+molar constants, viz.  $\{e, m_e, k_B; \epsilon_0, \mu_0; N_A, f_A\}$ . All other constants are derived from them.

**Table 13.** EM Planck units reformulated in terms of the subset of derivative units  $\{M_P, G, c, Z_0\}$ .<sup>\*</sup> The EM units are simplified considerably by the introduction of the effective gravitational constants  $G_\star = G/K = 4\pi\epsilon_0 G$  (electric) and  $G_B = GK/c^2 = G\mu_0/(4\pi)$  (magnetic).

Unit	Symbol	Planck Definition	Reformulation <sup>**</sup>
Charge	$Q_P$	$Q_P = \sqrt{h c/K}$	$Q_P = M_P\sqrt{G_\star}$
Magnetic Flux	$\Phi_P$	$\Phi_P = \sqrt{K h/c}$	$\Phi_P = M_P\sqrt{G_B}$
Voltage	$\mathcal{V}_P$	$\mathcal{V}_P = \sqrt{K c^4/G}$	$\mathcal{V}_P = c^2/\sqrt{G_\star}$
Electric Current	$\mathcal{I}_P$	$\mathcal{I}_P = \sqrt{c^6/(GK)}$	$\mathcal{I}_P = c^2/\sqrt{G_B}$
Electric Resistance	$\mathcal{R}_P$	$\mathcal{R}_P = K/c$	$\mathcal{R}_P = Z_0/(4\pi)$
Capacitance	$C_P$	$C_P = \sqrt{h G/(K^2 c^3)}$	$C_P = G_\star M_P/c^2$ <sup>***</sup>
Inductance	$\mathcal{L}_P$	$\mathcal{L}_P = \sqrt{h G K^2/c^7}$	$\mathcal{L}_P = G_B M_P/c^2$ <sup>***</sup>

<sup>\*</sup>Our RPS set of fundamental units includes field+vacuum+molar constants, viz.  $\{e, m_e, k_B; \epsilon_0, \mu_0; N_A, f_A\}$ . All other constants are derived from them.

<sup>\*\*</sup>The reformulated units produce simple classical expressions for Planck's constant  $h$ : (1)  $h = GM_P^2/c$ , showing that  $h$  has dimensions of action; (2)  $h = G_\star M_P^2 \mathcal{R}_P$ , where the interplay between gravity and the vacuum constants in formulating the classical form of  $h$  becomes apparent; (3) the definition of the Planck charge implies the fundamental relation  $Q_P^2 = G_\star M_P^2$  which leads to  $h = Q_P^2 \mathcal{R}_P$ , where the interplay between EM forces and the vacuum becomes apparent. In a unified conservative field that contains two sources (mass  $G_\star M$  and charge  $Q$ ), such determinations leading to a unique value of  $h$  are not surprising.

<sup>\*\*\*</sup>Notably also  $C_P = (4\pi\epsilon_0)L_P$  and  $\mathcal{L}_P = \left(\frac{\mu_0}{4\pi}\right)L_P$ .

### 3. Classical Determinations of QED Constants

Based on the calculations summarized in Tables 1–11, we reformulate some of the important constants of quantum theory in classical terms. Our starting point is the reduced Avogadro number  $\mathfrak{N}_A \approx 6 \times 10^{22}$  and the associated Avogadro factor  $f_A \approx 10$ , the two new natural constants determined more precisely in Table 4. All by themselves, these fundamental constants yield simple expressions for the gravitational coupling  $\alpha_g \equiv Gm_e^2/(hc)$  and the relative strong coupling  $\beta_s \equiv \alpha_s/\alpha$ , respectively, viz.

$$\alpha_g = (\mathfrak{N}_A)^{-2}, \quad (10)$$

and

$$\beta_s = (f_A)^2. \quad (11)$$

Equation (11) is consistent with the fact that the strong coupling is stronger than the EM FSC coupling since  $f_A \gg 1$  and  $(f_A)^2$  is even larger. On the other hand, equation (10) supports the well-known view that gravity's coupling is extremely weak because there exist way too many particles in the universe. Equivalently, since

$$\alpha_g = \left(\frac{m_e}{M_P}\right)^2, \quad (12)$$

gravity's coupling is extremely weak because the mass of the electron is much smaller than the Planck mass.

Next, by combining equations (10) and (12), we cast the Planck mass in the convenient form

$$M_P = \mathfrak{N}_A m_e, \quad (13)$$

that will allow us to rewrite many of the equations of physics and all the Planck units in simple forms admitting straightforward interpretations. We reformulate thus some natural constants in the following subsections, a number of well-known QED equations in Section 4, and the Planck system of units in Section 5.

### 3.1. Planck's Constant $h$

Solving our  $h$ -defined equation for the Planck mass ( $M_P = \sqrt{h c/G}$ ) for  $h$ , we find that

$$h = \frac{G M_P^2}{c}, \quad (14)$$

where  $M_P$  is now defined by equation (13).

This form is not unexpected. It has not been discussed previously because there was no way to derive  $M_P$  without using  $h$ . Nevertheless, equation (14) is not the simplest form that can be obtained now. In Section 5, we obtain more forms, the simplest of which turns out to be

$$h = Q_P^2 \mathcal{R}_P, \quad (15)$$

where

$$Q_P = M_P \sqrt{G_\star}, \quad (16)$$

is the Planck charge. Evidently, Planck's  $h$  can be interpreted as a purely EM constant imprinted by the impedance of free space (equation (2)). This opens a new way of thinking about photons that have never before been thought to be subject to constraints set by the vacuum.

Equations (14) and (15) also lend support to the idea that there exists a unified conservative field responsible for both gravitational and Coulomb long-range forces—because different subsets of the field properties produce consistently the same  $h$  value. Naturally, it is equation (16) that underwrites this consistent behavior.

### 3.2. Fine-Structure Constant $\alpha$

The definition of the FSC  $\alpha \equiv Ke^2/(hc)$  is recast in the classical form

$$\alpha = \frac{e^2}{G_\star M_P^2}. \quad (17)$$

where  $M_P$  is now defined by equation (13).

Since  $G_\star M_P^2 = Q_P^2$  (equation (16)), we rewrite equation (17) in the simplest possible form

$$\alpha = \left( \frac{e}{Q_P} \right)^2. \quad (18)$$

The correspondence between equations (12) and (18) is undeniable. We note, additionally, that the same ratios without the squares also have clear physical meanings, viz.  $\frac{m_e}{M_P} = (\aleph_A)^{-1}$  and  $\frac{e}{Q_P} = \alpha_w$ , respectively.

### 3.3. Relative Gravitational Coupling Constant $\beta_g$

The relative gravitational coupling constant  $\beta_g \equiv \alpha_g/\alpha$  [6] measures the relative strength of gravitational coupling against the measurable by experiment FSC. It is interesting that  $\beta_g$  is independent of the relative Avogadro number  $\aleph_A$  because the  $\alpha$ -couplings in its definition are both  $\propto (M_P)^{-2}$ . This is also seen in the equivalent expression in terms of the mass-to-charge ratio of the electron, viz.

$$\beta_g = G_\star \left( \frac{m_e}{e} \right)^2. \quad (19)$$

The relative ratio  $\beta_g$  is a minimum since  $G_\star \propto \varepsilon_0$  and  $\varepsilon_0$  is a universal lower limit.

### 3.4. Compton Radius $r_c$ of the Electron

Eliminating  $h$  from the  $h$ -defined Compton radius of the electron  $r_c = h/(m_e c)$ , we find that

$$r_c = \frac{GM_P^2}{m_e c^2}. \quad (20)$$

This relation admits the classical interpretation that the gravitational binding energy of two Planck masses separated by distance  $r_c$  is equal to the rest-energy of one electron.<sup>5</sup>

### 3.5. Landé $g_s$ -Factor of the Electron

Our rejection of  $\hbar$  in favor of Planck's  $h$  finds additional support from a well-known QED result, the "unambiguous and unambiguously correct determination" [58] of the first-order correction to the Landé  $g_s$ -factor of the anomalous magnetic moment of the electron [59,60], viz.

$$\frac{g_s - 2}{2} = (861.0225766)^{-1} = 1\alpha. \quad (21)$$

The calculation produced a pure numerical value of  $\mathcal{O}(\alpha) = 1\alpha$  (where  $\alpha$  is defined here in terms of  $h$  as in Table 7), but it was not recognized as such (e.g., [58]) because of the  $\hbar$ -defined FSC at that time. So, the erroneous geometric imprint of  $1/(2\pi)$  became the main result, the coefficient in the first-order correction that Schwinger [60] set out to determine by perturbation theory.

No-one noticed the suspicious appearance of the 2-D ( $2\pi$ ) term in this result: the magnetic moment and the spin of the electron are vectors, thus the Landé  $g_s$ -coefficient should have been a pure number, a scaling constant devoid of geometry, just like the zeroth-order factor  $(g_s)_0 = 2$  [61]. Thus, a reasonable interpretation of the result would have been the following:

- Assuming that the calculation was correct, the  $(2\pi)$  tag could not be eliminated by any means; but it could be absorbed in the FSC (ringing the bell that something was not set properly in the definition of that man-made constant at that time). That would have restored the FSC to the self-consistent form given in Table 7, and the correction to the Landé  $g_s$ -factor to the pure value of  $1\alpha$ .

## 4. Geometrically Clear QED Equations

Planck units not using  $\hbar$ , with Planck's  $h$  given by equation (14) and the Planck mass  $M_P$  defined by equation (13), simplify a large number of physical quantities and allow for unequivocal interpretations of the resulting equations. We summarize here five cases of general interest:

- ① The Bekenstein-Hawking formula for the entropy of a black hole of mass  $M_{\text{BH}}$  [62–64] is  $S_{\text{BH}} = k_B A / (2L_P)^2$ , where  $A$  is the area of its event horizon and  $L_P$  is the Planck length [20]. For a Schwarzschild black hole, we set its horizon area to  $A = 4\pi R_S^2$ , and we also define the Planck length in terms of  $h$ , not  $\hbar$  (Table 3); then, the Bekenstein-Hawking formula takes the concise form

$$S_{\text{BH}} = 4\pi k_B \left( \frac{M_{\text{BH}}}{M_P} \right)^2. \quad (22)$$

The factor of  $4\pi$  (the imprint of the 3-D space [6,32]) has emerged in this equation to denote that  $S_{\text{BH}}$  is the integrated entropy enclosed within the volume of the black hole. For a black hole with mass  $M_{\text{BH}} = m_e$ , equation (22) reduces to  $S_{\text{BH}} = 4\pi k_B \alpha_g$ , where  $\alpha_g = (\mathfrak{N}_A)^{-2}$ .

- ② The Bekenstein bound for the maximum entropy of a body of mass  $M$ , radius  $R$ , and rest-energy  $E$  [65–69] is  $S_{\text{max}} = k_B (2\pi R) E / (hc)$ . Written in this form, the equation gives a misleading signal (i.e., the circumference  $(2\pi R)$  is a 2-D quantity), although it reduces to equation (22) for a black hole

with  $R = R_S$  and  $E = c^2 M_{\text{BH}}$ . The apparent geometric issue is resolved when  $S_{\text{max}}$  is reformulated in terms of the Planck mass: using equation (14) to eliminate  $(hc)$  from  $S_{\text{max}}$ , we find that

$$S_{\text{max}} = 4\pi k_B \left( \frac{R}{R_S} \right) \left( \frac{M}{M_P} \right) \left( \frac{E}{E_P} \right), \quad (23)$$

where  $E_P = c^2 M_P$  is the Planck energy. The appearance of the comparative ratio  $R/R_S$  asserts the fundamental nature of the Schwarzschild radius  $R_S$  [67–69] (in contrast to the man-made Planck length  $L_P$ ), including the natural (i.e., not man-made) factor of 2 that appears in the definition  $R_S \equiv 2GM/c^2$ : introducing the ratio  $R/L_P$  in equation (23) leads to a simpler formula, viz.

$$S_{\text{max}} = 2\pi k_B \left( \frac{R}{L_P} \right) \left( \frac{E}{E_P} \right), \quad (24)$$

which, however, displays the apparent  $2\pi$  geometric issue previously discussed, arising from the subjective definition of the Planck length.

- ③ The thermal Hawking temperature of a black hole (also called Hawking-Unruh or Davies-Unruh temperature in related contexts) [70–73] is defined here as  $\Theta_{\text{BH}} = ha/(k_B c)$ , where  $a$  denotes acceleration. As usual, this definition is given in terms of  $h$  (not  $\hbar$ ), but it is also devoid of a man-made factor<sup>6</sup> of  $(2\pi)^2$ . For a Schwarzschild black hole of mass  $M_{\text{BH}}$  and surface acceleration of  $a = GM_{\text{BH}}/R_S^2 = c^4/(4GM_{\text{BH}})$  on the horizon, we find a concise formula for  $\Theta_{\text{BH}}$ , viz.

$$\frac{\Theta_{\text{BH}}}{\Theta_P} = \frac{1}{4} \left( \frac{M_{\text{BH}}}{M_P} \right)^{-1}, \quad (25)$$

where  $\Theta_P = c^2 M_P/k_B$  is the Planck temperature. The factor of  $1/4$  stems from the maximum relativistic tension force [74–77], viz.

$$F_{\text{max}} = \frac{c^4}{4G}, \quad (26)$$

which is realized on the horizon  $R = R_S$  of the Schwarzschild black hole, where the acceleration is  $a = F_{\text{max}}/M_{\text{BH}}$ .

- ④ A new deeper interpretation of Heisenberg's position-momentum  $(x, p_x)$  uncertainty principle [78–80] emerges from equations (14) and (15):
- Written in the standard form  $\Delta x \Delta p_x \geq \hbar/2$ , the inequality is misleading: Dirac's  $\hbar$  is a 2-D constant, whereas the standard deviations  $(\Delta x, \Delta p_x)$  are 1-D uncertainties. This recurring issue with  $\hbar$  was exposed and explored in Ref. [6] for the first time. Thus, we write the uncertainty principle in an unambiguous form as

$$\Delta x \Delta p_x \geq \frac{h}{4\pi}, \quad (27)$$

that shows a 3-D vacuum tag of  $4\pi$ , a signature that the 1-D motion actually unfolds within the 3-D space.

- Although the geometry in equation (27) is now clear, there is another issue that has not heretofore been discussed: Planck's  $h$  has been introduced as a lower limit without justification or explanation of its minimum value. In fact, up until now,  $h$  has been thought as a constant threshold; perhaps like the vacuum impedance  $Z_0$  and MOND's critical acceleration  $a_0$ , and certainly unlike the limiting values  $c$ ,  $\epsilon_0$ , and  $\mu_0$ .
- This issue is resolved by considering either one of equations (14) and (15). The lower bound in Heisenberg's inequality, viz.  $h/(4\pi)$ , is then understood in two fully consistent ways:
  - (a) Equation (14) shows that  $h \propto 1/c$ , hence  $h$  attains a minimum value in the natural world because  $c$  is an upper limit.

- (b) Equation (15) points to the same conclusion. The Planck resistance is a threshold to be matched from above or below for efficient radiation transmission (see, e.g., [81]). But then,  $h \propto Q_P^2 \propto G_* \propto \varepsilon_0$ , hence  $h$  is minimized by the vacuum.<sup>7</sup>

It is interesting to note that, in contrast to Planck's  $h$  and gravity's  $\alpha_g$ , the dimensionless couplings  $\alpha$ ,  $\alpha_w$ , and  $\alpha_s$  attain maximum values. In the ordered list  $\alpha_g < \alpha < \alpha_w < \alpha_s$ , the reduced Avogadro number and its factor set the extreme values at the two ends, and the vacuum enhances the values of the electroweak constants in the middle.<sup>8</sup>

- ⑤ The Casimir force per unit area between two parallel conducting plates [82] has occupied many physicists over the past 80 years. Its magnitude was determined by several different methods (e.g., [82–86]), and it was confirmed experimentally to  $\leq 1\%$  accuracy (e.g., [87–89], and references therein). The Casimir effect was originally thought to be a quantum effect that originates from vacuum energy fluctuations and provides proof that zero-point energies in quantum-field ground states are real. These notions were conclusively refuted [86,90,91], except for the quantum nature of the effect ( $\hbar$  is present in the equations). In our times, the Casimir force is believed to be the relativistic analogue of the classical van der Waals force in which retardation effects are taken into account [86,90–95], and it is produced by the matter-EM interaction term in the QED Hamiltonian [90].

Here, we revisit the Casimir effect in light of our results:

- Equations (13)–(15) highlight the classical origin of Planck's  $h$ , thereby dispelling the notion that the nature of the Casimir force lies in quantum mechanics. Thus, this force is the classical van der Waals force [92,96] corrected to account for the finite speed of light.
- Another issue concerns the appearance of geometric terms in the equations for the Casimir effect. The full treatment of the effect shows  $2\pi$ -dependent coefficients introduced by counting the density of states along the principal directions on the surfaces of the plates, which does not raise any concerns. Expressed in terms of the Planck unit of pressure  $P_P = c^2 M_P / L_P^3$ , the Casimir pressure  $P_c$  is given by

$$P_c = -\frac{\pi}{480} \frac{GM_P^2}{d^4} = -\frac{\pi}{480} P_P \left(\frac{L_P}{d}\right)^4, \quad (28)$$

where  $d$  is the distance between the flat, parallel, perfectly conducting plates. The final  $\pi$  term effectively arises from the quotient of the density of states  $\propto (2\pi)^2$  to the area  $\propto \pi$ . No other factors of  $\pi$  appear in the integration over  $d$  to find the binding energy of the plates.

- On the other hand, the simplified 1-D scalar analogue of the effect [85,86] should not contain any geometric terms, which is indeed the case for the 1-D Casimir force  $F_c$ , viz.

$$F_c = -\frac{1}{48} \frac{GM_P^2}{d^2} = -\frac{F_{\max}}{12} \left(\frac{L_P}{d}\right)^2, \quad (29)$$

where  $F_{\max} = F_P/4$  is given by equation (26) above.

## 5. Reformulated Planck System of Units

Equations (13)–(15) support a reformulation of the conventional Planck system of units [1,2,20] in terms of the fundamental RPS set of universal (field+vacuum+molar) constants

$$\text{RPS} := \{ e, m_e, k_B; \varepsilon_0, \mu_0; N_A, f_A \}. \quad (30)$$

Of those, only the Avogadro factor ( $f_A = 10.0553\ 0213$ ;<sup>9</sup> Table 4) is an unfamiliar constant. All other natural constants, including  $G$  (Table 2),  $h$  (equations (13)–(15)), and the dimensionless couplings (Table 8), can be derived from this fundamental set, starting with  $\aleph_A = N_A/f_A$ ,  $M_P = \aleph_A m_e$ , and following with the other equations given in Section 3 above.

The original (mechanical) Planck units are listed in Table 12, and the extended (EM) units are listed in Table 13, along with the corresponding RPS units shown in the last column of each table. Mechanical RPS units in Table 12 are given in terms of a subset of units that includes Boltzmann's  $k_B$  and the derivatives  $\{M_P, G, c\}$ . EM RPS units in Table 13 are given in terms of a subset of units that includes the derivatives  $\{M_P, G_\star, G_B, c, Z_0\}$ . As seen in Tables 1 and 2, Boltzmann's constant and the gravitational constants carry entropy information where they appear.

The effective gravitational constants  $G_\star$  and  $G_B$  appear in the units of Table 13 in a systematic way:  $G_\star$  appears in electrostatic units, whereas  $G_B$  appears in magnetic units associated with current flows. This distinction is also seen in the SI units of the two constants:

- The SI unit of  $\sqrt{G_\star}$  is  $C\text{ kg}^{-1}$ , hence this constant represents a charge-to-mass ratio. Thus,  $\sqrt{G_\star}$  could be an integral part of a unified conservative long-range field that would combine the sources of mass and charge.
- The SI unit of  $\sqrt{G_B}$  is  $(\text{m}^2\text{ s}^{-1})\text{ C}^{-1}$ , hence this constant represents areal flux per unit charge.

The above constants are composite, so their squares roots represent G-Ms. Combined, they also form two new G-Ms. The roles of the various G-M derivatives are elucidated below.

### 5.1. The Geometric Means $\sqrt{G_\star}$ and $\sqrt{G_B}$

(a) The composite constant  $G_\star$  (equation (4)) appeared in an effort to bring Gauss's law into precise correspondence between the gravitational field and the electrostatic field [32], but its G-M  $\sqrt{G_\star}$  gave us the motivation to pursue the present research by revealing a numerical connection between this G-M and  $k_B/e$  (Tables 1 and 2), viz.

$$\mathcal{N}(\sqrt{G_\star}) = \frac{\mathcal{N}(k_B)}{\mathcal{N}(e)} \times 10^{-6}, \quad (31)$$

followed by the additional relations pertaining to MOND constants that, for all practical purposes, show that  $\mathcal{N}(\mathcal{A}_0) = \mathcal{N}(G_\star)$  and  $\mathcal{N}(a_0) = \mathcal{N}(4\pi\epsilon_0)$  (Table 5).

(b) The composite constant  $G_B$  (equation (5)) appeared in the reformulation of the EM Planck units (Table 13), where it simplified greatly the new RPS units. Its G-M  $\sqrt{G_B}$  carries precisely the same information as  $\sqrt{G_\star}$ , although it is scaled by a different vacuum constant, viz.

$$\sqrt{G_B} = \mathcal{R}_P \sqrt{G_\star} = \frac{Z_0}{4\pi} \sqrt{G_\star}. \quad (32)$$

### 5.2. The Geometric Means of $G_\star$ and $G_B$

(a) The G-M of  $G_B$  and  $1/G_\star$  is obtained from equation (32), viz.

$$\sqrt{\frac{G_B}{G_\star}} = \mathcal{R}_P. \quad (33)$$

In the form of the Planck resistance  $\mathcal{R}_P$ , this G-M is multitasking in EM relations, as it appears in the units of Ohm's law  $\mathcal{V}_P/\mathcal{I}_P = \mathcal{R}_P$ , the units of the magnetic flux  $\Phi_P/Q_P = \mathcal{R}_P$  in Faraday's law, and the RLC circuit units of  $\mathcal{L}_P/C_P = \mathcal{R}_P^2$  (Table 13). Furthermore, it is easy to show that  $\sqrt{G_B/G_\star} = K/c$ , where  $K = 1/(4\pi\epsilon_0)$  is Coulomb's constant. This relation is useful for comparison with the other G-M discussed just below.

(b) The other G-M obtained from the product of  $G_B$  and  $G_\star$  is certainly related to Newton's  $G$ . A simple reduction yields the relation  $\sqrt{G_B G_\star} = G/c$ .

Finally, combining the two G-Ms, we obtain the unfamiliar magnetic relation mentioned in Table 13 that  $G_B = GK/c^2$ . From this form, we can also derive the G-M of  $G$  and  $K$ , viz.

$$\sqrt{GK} = c\sqrt{G_B}, \quad (34)$$

also unfamiliar in physical theory. This G-M could provide the constant of interaction between mass and charge in a unified conservative long-range field [97].

## 6. Discussion and Conclusions

### 6.1. Results

In Section 1, we categorized and summarized some conceptual pitfalls impacting physical theory and the significant benefits that can be gained from their resolution. The most important empirical results from this investigation (Tables 1–13) are the following:

- Dirac's  $\hbar$  should be recognized for what it is (a 2-D composite constant appropriate for planar orbits), and it should not be used in 3-D settings such as the coupling constants and the Planck units, where Planck's  $h$  is the correct constant to be used. When this is done, several 'pieces of the puzzle' fall into place:
- The  $h$ -defined FSC  $\alpha \approx 1/861$  displays number 861 that can be interpreted physically [6], very much unlike the unphysical 137 that has tormented many physicists in the past [53,54].
- The Planck mass  $M_P = \aleph_A m_e$  is related to the electron mass  $m_e$  via a reduced Avogadro number  $\aleph_A = N_A/f_A$  which also determines uniquely the gravitational coupling constant  $\alpha_g = 1/(\aleph_A)^2$ .
- The gravitational interaction (quantified via  $\alpha_g$ ) is extremely weak in nature because there exist way too many particles ( $\aleph_A \gg 1$ ).
- The Avogadro factor  $f_A$  effectively determines the strong coupling constant  $\alpha_s = (f_A)^2 \alpha$ . Equivalently, the relative ratio  $\beta_s \equiv \alpha_s/\alpha$  is determined solely from  $f_A$ , viz.  $\beta_s = (f_A)^2 \gg 1$ .
- The weak coupling constant turns out to be  $\alpha_w = \sqrt{\alpha}$ , indicating that electroweak theory actually has only one coupling constant.
- The mass of the W boson is determined to high precision from the reduced Fermi constant and the FSC (Table 9). The mass of the Higgs boson is also found by a G-M in Section 6.2 below.
- Fundamental QED constants such as Planck's  $h$ , the FSC, and the Compton radius of the electron are found to be derivatives that have a classical origin (Section 3); whereas classical Avogadro numbers such as  $\aleph_A$  and  $f_A$  appear to be fundamental natural constants.
- The RPS set of (field+vacuum+molar) constants  $\{e, m_e, k_B; \epsilon_0, \mu_0; N_A, f_A\}$  appears to be a fundamental set of units that produces an uncomplicated, easy-to-use reformulation of the original Planck system of units (Tables 12 and 13).
- Using EM RPS units (Table 13), Planck's constant can be written in the simplest possible classical form, viz.  $h = Q_P^2 \mathcal{R}_P$ . Hence,  $h$  can be interpreted as a purely EM constant modified only by the impedance of free space (equation (2)).
- The G-M of the Planck charge  $Q_P$  and the elementary charge  $e$  produces a new intermediate charge  $Q_\star$ . The resulting geometric sequence  $\{e < Q_\star < Q_P\}$  has an unusual common ratio of  $\alpha_w^{-1/2} \approx 5.4169$  (since  $e/Q_P = \alpha_w$ ). The significance (if any) of charge  $Q_\star$  is not clear.
- The value of Newton's gravitational constant  $G$  is determined from the values of Boltzmann's constant  $k_B$ , the elementary charge  $e$ , and the vacuum constant  $4\pi\epsilon_0$  (Table 2).
- Two new effective gravitational constants are defined by combining  $G$  with vacuum constants, viz.  $G_\star = G(4\pi\epsilon_0)$  and  $G_B = G(\frac{\mu_0}{4\pi})$ , that are related by  $G_B = \mathcal{R}_P^2 G_\star$ . They are both minimum values since  $\epsilon_0$  and  $\mu_0$  are lower limits in nature.
- All constants determined in terms of Newton's  $G$  carry entropy-related embedded information. The numerical coefficient of the exact SI value of Boltzmann's constant (1.380649 [12,13]) appears explicitly in the values of the G-M  $\sqrt{e^2 G_\star}$  and the charge radius of the electron  $R_e$  [37] (or, equivalently, the Stoney length  $L_S$  [28]; Table 11). This is the first time that entropy considerations have been seen in a linear (1-D) setting.
- Numerous physical constants and two of 4 vacuum constants are determined from G-M averages involving other universal constants [6,35,36]. Several cases have been highlighted in the main text, and the key G-M  $\sqrt{e^2 G_\star}$  was just mentioned above. In this regard, the other G-M of  $e^2$  and  $G_\star$  (i.e., the Stoney mass  $M_S$ ) is not well-known and is discussed below in Appendix B. A complete list of all related constants is summarized in Appendix C.
- The source of the gravitational field in Newtonian dynamics and in MOND [32–34,49] has the same strength, viz.  $\mathcal{N}(\mathcal{A}_0 M) = \mathcal{N}(G_\star M)$  for a mass  $M$  (Appendix A). But the MOND force is

- modified by an overlaid square root, in which case the units of the effective gravitational constant are modified accordingly, but not its numerical value.
- MOND's modification of the source of gravity  $\mathcal{A}_0 M$  by a square root [49] is analogous to  $\sqrt{\alpha}$  producing the value of  $\alpha_w$  (even though  $\mathcal{A}_0$  is not unitless). This analogy could not have been made until recently [6,32] for the relation  $\alpha_w = \sqrt{\alpha}$  was not known.
  - For the MOND threshold acceleration  $a_0$ , we then find a non-cosmological 'vacuum' value of  $\mathcal{N}(a_0) = \mathcal{N}(4\pi\epsilon_0)$ , falling well within the error bar of recent astrophysical measurements [109,110].

### 6.2. Universal Masses

Nature seems to recognize  $\aleph_A \approx 6.0 \times 10^{22}$  as fundamental constant and the inverse Avogadro factor  $f_A^{-1} \approx 0.10$  as a universal molar unit (Table 4). Then, the Planck mass  $M_P = \aleph_A m_e$  is asserted as an important mass scale (Table 3), and the mass of the electron  $m_e$  is recognized as a fundamental natural unit (Section 5).

There are several notable relations involving these masses:

- The mass ratio  $m_e/M_P$  is a measure of the strength of gravity (equation (12)).
- The G-M  $\sqrt{m_e M_P}$  is a multiple of the Higgs mass  $m_H$  [31], viz.  $\sqrt{m_e M_P} = 10^6 m_H$  accurate to within 0.12% (see Appendix C for details).
- The scaling  $M_P \alpha_w$  produces the Stoney mass  $M_S$  at which the relative gravitational coupling  $\beta_g = 1$  (Appendix B).
- The scaling  $m_e/\alpha_w$  produces a new subatomic mass scale  $M_{\text{sub}} = 14.9943\ 3735\ \text{MeV}/c^2$  that lies between the masses of the light quarks.
- Mass  $M_{\text{sub}}$  was first obtained from a scaling of the Planck mass, viz.  $M_{\text{sub}} = M_P \sqrt{\beta_g}$  [6], where  $\beta_g$  is defined by equation (19).

The involvement of the weak coupling constant  $\alpha_w$  may not be a surprise [6]. It is plausible that  $\alpha_w = \sqrt{\alpha}$  also comes from a ratio of masses of elementary particles: using the most recent PDG values [31] for the masses of the bottom quark ( $m_b$ ) and the Higgs boson ( $m_H$ ), we find that  $m_b/m_H = 3.3411(63) \times 10^{-2}$ , lower by 1.5% than the PDG world average of  $\alpha_w$  (notes to Table 8). This supports the relation  $\alpha = (m_b/m_H)^2$  which is analogous to that of equation (12), viz.  $\alpha_g = (m_e/M_P)^2$ .

### 6.3. Universal Charges

Along similar lines to the masses above, the Planck charge  $Q_P = M_P \sqrt{G_\star}$  is asserted as an important charge scale (Table 3), and the elementary charge  $e$  is recognized as a fundamental natural unit (Section 5).

There are some notable relations involving these charges as well:

- The charge ratio  $e/Q_P$  is a measure of the strength of the electroweak interaction (viz.  $(e/Q_P)^2 = \alpha$  and  $e/Q_P = \alpha_w$ , respectively).
- The G-M  $\sqrt{e Q_P}$  is a new charge  $Q_\star$  whose significance is not yet known.
- The Planck charge  $Q_P \propto \sqrt{\epsilon_0}$  appears to be a minimized value ( $\epsilon_0$  is a lower limit), although the other two charges lie below this minimized threshold.

**Author Contributions:** The authors have worked on all aspects of the problems, and all read and agreed to the published version of the manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

**Funding:** DMC and SGTL acknowledge support from NSF-AAG grant No. AST-2109004.

**Data Availability Statement:** The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

**Acknowledgments:** NASA, NSF, and LoCSST support over the years is gratefully acknowledged by the authors.

## Abbreviations

The following abbreviations are used in this manuscript:

CDF	Collider Detector at Fermilab
CODATA	Committee On Data
EM	ElectroMagnetic
FJ	Faber-Jackson [106]
FSC	Fine-Structure Constant
G-M	Geometric-Mean
MOND	MODified Newtonian Dynamics
PDG	Particle Data Group
ppm	parts per million
QED	Quantum ElectroDynamics
RLC	Resistance-Inductance-Capacitance (circuit)
RPS	Reformulated Planck System
SDs	Significant Digits
SI	Système International d'unités
TF	Tully-Fisher [103]
1-D, 2-D, etc.	one-dimensional, two-dimensional, etc.

## Appendix A. MOND Universal Constants

In MOND, as well as in varying- $G$  gravity, a fundamental constant appears besides Newton's  $G$  [33–35,49,98–102], and it is the only constant that remains in the so-called deep MOND limit in which the Newtonian force is neglected [33,34]. In the deep MOND limit,  $G \rightarrow 0$  and the critical acceleration  $a_0 \rightarrow \infty$ , while the product  $\mathcal{A}_0 = a_0 G$  remains finite. The dimensions of  $\mathcal{A}_0$ , viz.  $[v]^4/[M]$ , are reminiscent of the baryonic Tully-Fisher (TF) [103–105] and Faber-Jackson (FJ) relations [106–108], galactic relations that are naturally explained by these theories of modified dynamics and modified gravity.

Constant  $\mathcal{A}_0$  has been previously determined approximately from the measured value of Newton's  $G$  and an average critical value of  $a_0 = 1.20 \times 10^{-10} \text{ m s}^{-2}$  obtained from observed spiral galaxy rotation curves. The errors are  $\pm 0.24 \times 10^{-10} \text{ m s}^{-2}$  (systematic) and  $\pm 0.02 \times 10^{-10} \text{ m s}^{-2}$  (random) [109,110]. We, on the other hand, have determined the values of  $\mathcal{A}_0$  and  $a_0$  from the numerical values of  $\mathcal{N}(G_\star)$  and  $\mathcal{N}(4\pi\epsilon_0)$ , respectively (Table 5), with the value of  $a_0$  falling well within the observational error bar.

The numerical concurrence between  $G_\star$  and  $\mathcal{A}_0$  (at a level of 21 orders of magnitude below unity) is not a coincidence. It occurs because  $a_0$  and  $4\pi\epsilon_0$  have equal magnitudes (apart from units). This results in the same strength of the source of the gravitational field in Newtonian dynamics and in MOND as well, viz.

$$\mathcal{N}(\mathcal{A}_0 M) = \mathcal{N}(G_\star M), \quad (\text{A1})$$

for the same mass  $M$ ; although the MOND force is also modified by a square root which is responsible for the different units between  $\mathcal{A}_0$  and  $G_\star$  [32]. Thus, there is no need for an equivalence principle of masses in MOND either [49].

The physical interpretation of  $\mathcal{A}_0 = a_0 G$  is as follows [6,34,49]:  $\mathcal{A}_0$  is the proportionality constant in the TF and FJ relations [103–108], viz.

$$v^4 = \mathcal{A}_0 M, \quad (\text{A2})$$

where  $v$  is speed. This raises the question of interpreting the other universal constant  $G_\star = 4\pi\epsilon_0 G$  in the same context: In the EM Planck system of units (Table 13), there is only one unit defined in terms of  $c$  and  $G_\star$ , the unit of voltage  $\mathcal{V}_p = c^2/\sqrt{G_\star}$ . By dimensional analysis, we thus obtain a “TF/FJ-like relation” for the square of the voltage  $\mathcal{V}$ , viz.

$$v^4 = G_\star \mathcal{V}^2. \quad (\text{A3})$$

Combining equations (A2) and (A3), we find in SI units that

$$\mathcal{V} = \left( \frac{M}{1 \text{ kg}} \right)^{1/2} \text{ V}. \quad (\text{A4})$$

Although it may prove unfeasible to test this relation in individual galaxies, the scaling works for the universe as a whole in a compelling way: Using  $M = c^4/\mathcal{A}_0 = 1.08777 \times 10^{54}$  kg for the mass of the universe in the cosmological system of units  $\{c, G, a_0\}$  [6], then equation (A4) returns the Planck voltage

$$\mathcal{V}_P = \frac{c^2}{\sqrt{G_\star}} = 1.042\,962\,076 \times 10^{27} \text{ V}. \quad (\text{A5})$$

This congruence occurs because of the equality (A1).

## Appendix B. The geometric Mean $\sqrt{e^2 G_\star^{-1}}$ and Comments on Physical Numerology

*Appendix B.1. The Stoney mass  $M_S$  and the Gravitational Source of the Electron  $G_\star m_e$*

The mostly neglected G-M of  $e^2$  and  $G_\star^{-1}$  has dimensions of [mass], and it appears in Table 11 as the Stoney mass [111]. Thus, we have

$$M_S = \sqrt{e^2 G_\star^{-1}}. \quad (\text{B1})$$

The Stoney units of mass and length can be obtained from the corresponding Planck units by multiplication by  $\alpha_w$  [25,111], so we also have  $M_S = M_P \alpha_w$ . Furthermore, the value of  $M_S$  can be obtained from the numerical equality

$$\mathcal{N}(M_S) = \frac{\mathcal{N}(e)^2}{\mathcal{N}(k_B)} \times 10^6, \quad (\text{B2})$$

leading to the additional equality

$$\mathcal{N}(G_\star M_S) = \mathcal{N}(k_B) \times 10^{-6}, \quad (\text{B3})$$

that offers a clear interpretation of the gravitational source term  $G_\star M_S \propto k_B$ , or  $G_\star M_P \propto k_B/\alpha_w$ , or, for the tangible electron,

$$G_\star m_e \propto \frac{k_B}{\alpha_w \mathfrak{N}_A}. \quad (\text{B4})$$

The gravitational source carries entropy, but it is exceptionally weak because there are way too many particles in the universe, limiting the field to effectively one (microscopic or macroscopic) state; that is,  $W = \exp [10^{-6}/(\alpha_w \mathfrak{N}_A)] \rightarrow 1^+$  in Boltzmann's entropy, so that  $\ln W = 10^{-6}/(\alpha_w \mathfrak{N}_A)$ .

*Appendix B.2. Physical Interpretations of  $M_S$  and the FSC*

Equation (B1) implies that the attractive Newtonian force between two Stoney masses separated by distance  $r$  has the same magnitude as the repulsive Coulomb force between two electrons or protons at the same distance  $r$ , viz.  $GM_S^2/r^2 = Ke^2/r^2$ .

Furthermore, mass  $M_S$  has significance for particle physics as well: It was first obtained in Ref. [6] from a different perspective (the unification of coupling constants [112,113]), and it was then expressed in atomic units of  $(\text{GeV})/c^2$ . The argument was that, if the coupling constants are running at higher energies, then the gravitational coupling constant  $\alpha_g$  meets the FSC (i.e.,  $\beta_g = 1$ ) at the critical mass  $M_S = 1.042\,962\,076 \times 10^{18} (\text{GeV})/c^2$ .<sup>10</sup> Thus, the Stoney mass  $M_S$  may also be determined from equation (19) by letting  $\beta_g \rightarrow 1$  and  $m_e \rightarrow M_S$ .

Finally, the Stoney units of mass and length afford another physical interpretation of the FSC: By multiplying  $M_S = M_P \alpha_w$  by  $L_S = L_P \alpha_w$ , we obtain the relation

$$\alpha = \frac{K e^2 / r_c}{m_e c^2}, \quad (\text{B5})$$

where the Compton radius  $r_c$  of the electron is given by equation (20). We see then that the FSC represents the ratio of the electrostatic potential energy of two elementary charges separated by distance  $r_c$  to the rest-energy of one electron.<sup>11</sup>

### Appendix B.3. Physical Numerology and Force Unification

Precise numerical relations between physical constants that carry different units, such as those described by equations (A1), (B2), and (B3), cannot probably be categorized to either one of the two classes of numerological formulae specified by I. J. Good [114]. In 1990, Good wrote:

“When a numerological formula is proposed, then we may ask whether it is *correct*. The notion of *exact correctness* has a clear meaning when the formula is purely mathematical, but otherwise some clarification is required. I think an appropriate definition of *correctness* is that the formula has a good explanation, in a Platonic sense, that is, the explanation could be based on a good theory that is not yet known but ‘exists’ in the universe of possible reasonable ideas.”

The numerical equalities discussed in this work are certainly *exactly correct*, yet they do require physical backing. Our understanding is that nature applies constraints with the same strength (and rebrands constants by taking their square roots) in different physical settings that researchers tend to analyze separately and in isolation from the general realm of the physical sciences.

This is an important assertion: We believe that force unification would not be viable without considering such a wider context across fields of physics and without limiting the number of independent constants at all physical scales. In this respect, the determination of G-M relations between natural constants (Tables 1–11 above and Refs. [32,35,97,111]) and between the 19 free parameters of the Standard Model of particle physics [6] appears to be a step in the right direction. This new methodology is expected to help substantially in the formulation of a comprehensive Lagrangian for the unified field that would depend on just a few ad-hoc coupling constants to describe all particle interactions.

## Appendix C. A Comprehensive List of Related Physical Constants

The physical constants investigated in this work are summarized in Tables A1 and A2. The constants are divided into fundamental and derivatives, respectively. Input values have been obtained from the CODATA [13] and the PDG [31] catalogues. Additional Planck units are listed in Tables 12 and 13 of the main text.

**Table A1.** List of the seven fundamental physical constants The set is defined in equation (30). The first six constants were taken from CODATA [13], whereas  $f_A$  was determined in this work.

Constant	Symbol	SI Value	SI Unit
FIELD CONSTANTS			
Elementary charge	$e$	$1.602\ 176\ 634 \times 10^{-19}$	C
Electron mass	$m_e$	$9.109\ 383\ 7139 \times 10^{-31}$	kg
Boltzmann's constant	$k_B$	$1.380\ 649 \times 10^{-23}$	J K <sup>-1</sup>
VACUUM CONSTANTS			
Vacuum permittivity	$\epsilon_0$	$8.854\ 187\ 8188 \times 10^{-12}$	F m <sup>-1</sup>
Vacuum permeability	$\mu_0$	$4\pi \times 10^{-7}$	N A <sup>-2</sup>
MOLAR CONSTANTS			
Avogadro number	$N_A$	$6.022\ 140\ 76 \times 10^{23}$	—
Avogadro factor	$f_A$	10.0553 0213	—

**Table A2.** List of derived physical constants. The function  $N(x)$  captures the numerical value of  $x$ .\*

Constant	Symbol	Equation	SI Value	SI Unit
VACUUM				
Speed of light	$c$	$c = 1/\sqrt{\epsilon_0\mu_0}$	$2.9979\ 2458 \times 10^8$	$\text{m s}^{-1}$
Planck resistance	$\mathcal{R}_P$	$\mathcal{R}_P = Z_0/(4\pi)$	$2.9979\ 2458 \times 10^1$	$\Omega$
Coulomb's constant	$K$	$K = 1/(4\pi\epsilon_0)$	$8.987\ 551\ 786 \times 10^9$	$\text{m}^3 \text{kg s}^{-2} \text{C}^{-2}$
GRAVITY				
Effective $G_\star$	$G_\star$	$N(G_\star) = N(10^{-6}k_B/e)^2$	$7.425\ 843\ 255 \times 10^{-21}$	$\text{C}^2 \text{kg}^{-2}$
Newton's constant	$G$	$G = G_\star/(4\pi\epsilon_0)$	$6.674\ 015\ 081 \times 10^{-11}$	$\text{m}^3 \text{kg}^{-1} \text{s}^{-2}$
Effective $G_B$	$G_B$	$G_B = G\mu_0/(4\pi)$	$6.674\ 015\ 081 \times 10^{-18}$	$\text{m}^4 \text{s}^{-2} \text{C}^{-2}$
MOND fundamental	$\mathcal{A}_0$	$N(\mathcal{A}_0) = N(G_\star)$	$7.425\ 843\ 255 \times 10^{-21}$	$\text{m}^4 \text{kg}^{-1} \text{s}^{-4}$
MOND acceleration	$a_0$	$N(a_0) = N(4\pi\epsilon_0)$	$1.112\ 650\ 0562 \times 10^{-10}$	$\text{m s}^{-2}$
$h$ -DEFINED PLANCK UNITS				
Planck mass	$M_P$	$M_P = \sqrt{hc/G}$	$5.455\ 628\ 31 \times 10^{-8}$	$\text{kg}$
Planck length	$L_P$	$L_P = \sqrt{hG/c^3}$	$4.051\ 264\ 07 \times 10^{-35}$	$\text{m}$
Planck charge	$Q_P$	$Q_P = \sqrt{hc/K}$	$4.701\ 296\ 73 \times 10^{-18}$	$\text{C}$
NATURAL NUMBER OF PARTICLES				
Avogadro factor	$f_A$	$f_A = N_A m_e/M_P$	10.0553 0213	—
Reduced Avogadro #	$\mathfrak{N}_A$	$\mathfrak{N}_A \equiv N_A/f_A = M_P/m_e$	$5.989\ 020\ 203 \times 10^{22}$	—
Gravitational coupling	$\alpha_g$	$\alpha_g = (\mathfrak{N}_A)^{-2}$	$2.787\ 972\ 231 \times 10^{-46}$	—
FORCE COUPLINGS				
EM coupling (FSC)	$\alpha$	$\alpha = Ke^2/(hc)$	$(861.022\ 5766)^{-1}$	—
Weak coupling	$\alpha_w$	$\alpha_w = \sqrt{\alpha}$	$3.407\ 946\ 203 \times 10^{-2}$	—
Strong coupling	$\alpha_s$	$\alpha_s = (f_A)^2 \alpha$	$1.174\ 290\ 938 \times 10^{-1}$	—
RELATIVE COUPLING RATIOS				
Relative strong coupling	$\beta_s$	$\beta_s \equiv \alpha_s/\alpha = (f_A)^2$	101.109 1009	—
Relative weak coupling	$\beta_w$	$\beta_w \equiv \alpha_w/\alpha = 1/\sqrt{\alpha}$	29.3431 8620	—
Relative grav. coupling	$\beta_g$	$\beta_g \equiv \alpha_g/\alpha$	$2.400\ 507\ 034 \times 10^{-43}$	—
ELECTROWEAK RELATIONS				
Stoney length	$L_S$	$L_S \equiv \frac{\mu_0}{4\pi} \sqrt{e^2 G_\star} = L_P \alpha_w$	$1.380\ 649\ 000 \times 10^{-36}$	$\text{m}$
Stoney length	$L_S$	$N(L_S) = N(10^{-13}k_B)$	$1.380\ 649\ 000 \times 10^{-36}$	$\text{m}$
Stoney mass	$M_S$	$M_S \equiv \sqrt{e^2(G_\star)^{-1}} = M_P \alpha_w$	$1.859\ 248\ 778 \times 10^{-9}$	$\text{kg}$
Stoney mass	$M_S$	$N(M_S) = N(e^2/(10^{-6}k_B))$	$1.859\ 248\ 778 \times 10^{-9}$	$\text{kg}$
Gravitational source	$G_\star M_S$	$N(G_\star M_S) = N(10^{-6}k_B)$	$1.380\ 649\ 000 \times 10^{-29}$	$\text{C}^2 \text{kg}^{-1}$
W boson mass	$m_W$	$m_W = \sqrt{(\pi/G_F^0)(\alpha/2)^{1/2}}/c^2$	80.564 55	$(\text{GeV})/c^2$
Higgs boson mass	$m_H$	$m_H = 10^{-6}\sqrt{m_e M_P}$	125.054 089 **	$(\text{GeV})/c^2$
GEOMETRIC-MEAN RELATIONS				
G-M of $M_P$ and $k_{B,MJ}$	$Q_\star$	$N(Q_\star) = N(\sqrt{M_P(10^{-6}k_B)})$	$8.678\ 886\ 893 \times 10^{-19}$	$\text{C}$
G-M of $Q_P$ and $e$	$Q_\star$	$Q_\star = \sqrt{e Q_P}$	$8.678\ 886\ 893 \times 10^{-19}$	$\text{C}$
G-M of $Q_P$ and $1/e$	$\sqrt{Q_P/e}$	$\sqrt{Q_P/e} = (\alpha_w)^{-1/2}$	5.416 935 130	—
G-M of $G$ and $K$	$\sqrt{GK}$	$\sqrt{GK} = c\sqrt{G_B}$	$7.744\ 872\ 895 \times 10^{-1}$	$\text{m}^3 \text{s}^{-2} \text{C}^{-1}$
G-M of $G$ and $1/K$	$\sqrt{G_\star}$	$N(\sqrt{G_\star}) = N(10^{-6}k_B/e)$	$8.617\ 333\ 262 \times 10^{-11}$	$\text{C kg}^{-1}$

\*The numerical relations are simplified by introducing the unit  $k_{B,\text{MeV}} = (10^{-6}k_B/e) \text{MeV K}^{-1}$  (Table 2), e.g.,  $N(M_S) = N(e/k_{B,\text{MeV}})$  and  $N(\sqrt{G_\star}) = N(k_{B,\text{MeV}})$ . A more compact notation in terms of a 'reduced Boltzmann constant' is presented in auxiliary Table A3 below.

\*\*To be compared to the PDG [31] world average of 125.20(11) (GeV)/ $c^2$ . We note that the measured boson masses predict the electron's mass-to-charge ratio  $N(m_e/e) = N(\epsilon_0)(m_W/m_H)$  to within 0.0333% accuracy.

**Table A3.** The numerical relations in Table A2 that display entropy information explicitly are summarized here for comparison purposes. The equalities are simplified by introducing the ‘reduced Boltzmann constant’  $\mathcal{K}_B \equiv 10^{-6} k_B$ . The function  $\mathcal{N}(x)$  captures the numerical value of  $x$ .

Constant	Symbol	Equation	SI Value	SI Unit
Gravitational source	$G_\star M_S$	$\mathcal{N}(G_\star M_S) = \mathcal{N}(\mathcal{K}_B)$	$1.380\,649\,000 \times 10^{-29}$	$C^2 \text{ kg}^{-1}$
Stoney length	$L_S$	$\mathcal{N}(L_S) = \mathcal{N}\left(\frac{\mu_0}{4\pi} \mathcal{K}_B\right)$	$1.380\,649\,000 \times 10^{-36}$	m
G-M of $G$ and $1/K$	$\sqrt{G_\star}$	$\mathcal{N}(\sqrt{G_\star}) = \mathcal{N}(\mathcal{K}_B/e)$	$8.617\,333\,262 \times 10^{-11}$	$C \text{ kg}^{-1}$
Effective $G_\star$	$G_\star$	$\mathcal{N}(G_\star) = \mathcal{N}(\mathcal{K}_B/e)^2$	$7.425\,843\,255 \times 10^{-21}$	$C^2 \text{ kg}^{-2}$
G-M of $M_P$ and $\mathcal{K}_B$	$Q_\star$	$\mathcal{N}(Q_\star) = \mathcal{N}\left(\sqrt{M_P \mathcal{K}_B}\right)$	$8.678\,886\,893 \times 10^{-19}$	C
Stoney mass	$M_S$	$\mathcal{N}(M_S) = \mathcal{N}(e^2/\mathcal{K}_B)$	$1.859\,248\,778 \times 10^{-9}$	kg

Numerical values of man-made constants have been determined by using Planck’s  $h$  instead of Dirac’s  $\hbar$ , and Newton’s  $G$  precise to 10 SDs (Table 4) has been used throughout.

The numerical relations in Table A2 that show explicit dependencies on entropy ( $\sim k_B$ ) are summarized in auxiliary Table A3, where the equalities are simplified considerably by using the ‘reduced Boltzmann constant’  $\mathcal{K}_B$  such that  $\mathcal{K}_B \equiv 10^{-6} k_B$ . It seems as though the frequently occurring scaling factor of  $10^{-6}$  to  $k_B$  is dimensionless, as it also appears (in the absence of  $k_B$ ) in the G-M determination of the Higgs boson mass  $m_H = 10^{-6} \sqrt{m_e M_P}$  (Table A2). This prevents the assignment of units to this number that would have converted the numerical equalities in Tables A2 and A3 to actual dimensional equations.<sup>12</sup>

We do however note some important points in relation to this unitless factor of  $10^{-6}$ :

- The reduced Boltzmann constant  $\mathcal{K}_B = 10^{-6} k_B$  is not exotic in any sense. It would naturally replace Boltzmann’s  $k_B$  if the (man-made) Kelvin temperature scale were to be stretched by a factor of  $10^6$  (so that the thermal energy  $k_B \Theta$  would remain the same).
- The factor of  $10^{-6}$  in  $\mathcal{K}_B$  effectively introduces a lower unit of entropy in the relations of Table A3. Only the Stoney mass gets a boost from the lower  $\mathcal{K}_B$  because  $\mathcal{N}(M_S) \propto \mathcal{N}(\mathcal{K}_B)^{-1}$ .
- The three important masses in physics form the geometric progression  $\{m_e, 10^6 m_H, M_P\}$  with common ratio  $\sqrt{\mathcal{N}_A} \simeq 2.44725 \times 10^{11}$ . This ratio that describes a concise relation between the three masses effectively depends on the number of particles in the present universe.
- The G-M  $10^6 m_H$  describes the cumulative mass of one million Higgs bosons, so the mass of the Higgs boson  $m_H$  is not singled out in this sequence.
- One might imagine a hypothetical particle with rest-energy  $10^6 m_H c^2 \simeq 125$  PeV. This energy scale lies far beyond the reach of contemporary TeV collider experiments, but it may turn out to be relevant to detections of highly energetic cosmic rays in the PeV-EeV range (e.g., [116–118]) and ultra-energetic muons from cosmic neutrinos [119,120].

## References

1. Planck, M. 1899, About irreversible radiation processes. *Sitzungsberichte Der Preuss. Akad. Wiss.*, 440
2. Planck, M. 1900, Ueber irreversible Strahlungsvorgänge. *Ann. Phys.*, **4**, S.69
3. Dirac, P. A. M. 1926, On the theory of quantum mechanics. *Proc. R. Soc. Lond. A*, **112**, 661
4. Dirac, P. A. M. *The principles of quantum mechanics*; Oxford University Press: London, UK, 1930; p. 87
5. Schrödinger, E. 1926, Quantisierung als eigenwertproblem. *Ann. Phys.*, **384**, 361
6. Christodoulou, D. M., & Kazanas, D. 2023, The upgraded Planck system of units that reaches from the known Planck scale all the way down to subatomic scales. *Astronomy*, **2**, 235
7. Bunker, P. R., Mills, I. M., & Jensen, P. 2019, The Planck constant and its units. *J. Quant. Spectr. Rad. Transfer*, **237**, 106594
8. Leblanc, C., Malpuech, G., & Solnyshkov, D. D. 2021, Universal semiclassical equations based on the quantum metric for a two-band system. *Phys. Rev. B*, **104**, 134312
9. de Broglie, L. 1925, Recherches sur la théorie des Quanta. *Ann. Phys.*, **10(3)**, 22

10. Lévy-Leblond, J.-M. Theoretical physics: Between the laboratory and the world. In: E. Beltrametti et al. (eds.) *One Hundred Years of h*, Vol. 79, Italian Physical Society, Pavia, Italy, 2000; p. 211
11. Hartree, D. 1928, The wave mechanics of an atom with a non-Coulomb central field. Part I. Theory and methods *Math. Proc. Camb. Phil. Soc.*, **24**, 89
12. Tiesinga, E., Mohr, P. J., Newell, D. B., & Taylor, B. N. 2021, CODATA recommended values of the fundamental physical constants: 2018. *Rev. Mod. Phys.*, **93**, 025010
13. Mohr, P. J., Newell, D. B., Taylor, B. N., & Tiesinga, E. 2025, CODATA recommended values of the fundamental physical constants: 2022, *Rev. Mod. Phys.*, **97**, 025002
14. Jackson, J. D. *Classical Electrodynamics*; Wiley: New York, USA, 1962; p. 611
15. Wikipedia 2025a, Centimetre-gram-second system of units. Online at [https://en.wikipedia.org/wiki/Centimetre%E2%80%93gram%E2%80%93second\\_system\\_of\\_units](https://en.wikipedia.org/wiki/Centimetre%E2%80%93gram%E2%80%93second_system_of_units) (accessed on 22 August 2025)
16. Brown, R. J. C., Brewer, P. J., Pramann, A., Rienitz, O., & Güttler, B. 2021, Redefinition of the mole in the Revised International System of Units and the ongoing importance of metrology for accurate chemical measurements. *Anal. Chem.*, **93**, 12147
17. Christodoulou, D. M. 2016, Euclidean figures and solids without incircles or inspheres. *Forum Geometricorum*, **16**, 291
18. Wikipedia 2025b, Volume of an n-ball. Online at [https://en.wikipedia.org/wiki/Volume\\_of\\_an\\_n-ball](https://en.wikipedia.org/wiki/Volume_of_an_n-ball) (accessed on 24 August 2025)
19. Wikipedia 2025c, n-sphere. Online at <https://en.wikipedia.org/wiki/N-sphere> (accessed on 24 August 2025)
20. Elert, G. 2025, The physics hypertextbook. Online at <https://physics.info/planck/> (accessed on 24 August 2025)
21. Wikipedia 2025d, Ampère's circuital law. Online at [https://en.wikipedia.org/wiki/Amp%C3%A8re%27s\\_circuital\\_law](https://en.wikipedia.org/wiki/Amp%C3%A8re%27s_circuital_law) (accessed on 24 August 2025)
22. Wikipedia 2025e, Gauss's law. Online at [https://en.wikipedia.org/wiki/Gauss%27s\\_law](https://en.wikipedia.org/wiki/Gauss%27s_law) (accessed on 24 August 2025)
23. Hampshire, D. P. 2018, A derivation of Maxwell's equations using the Heaviside notation. *Philos. Trans. A Math. Phys. Eng. Sci.*, **376** (2134), 20170447
24. Wikipedia 2025f, Maxwell's equations. Online at [https://en.wikipedia.org/wiki/Maxwell%27s\\_equations](https://en.wikipedia.org/wiki/Maxwell%27s_equations) (accessed on 24 August 2025)
25. Duff, M. J., Okun, L. B., & Veneziano, G. 2002, Dialogue on the number of fundamental constants. *JHEP03*, 023
26. Zeidler, E. *Quantum field theory I: Basics in mathematics and physics*; Springer: Berlin/Heidelberg, Germany, 2006; pp. 931-953
27. Weinberg, S., & Taylor, J. G. 1983, Overview of theoretical prospects for understanding the values of fundamental constants. *Phil. Trans. R. Soc. London, Ser. A*, **310**, 249
28. Stoney, G. J. 1881, LII. On the physical units of nature. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, **11**(69), 381
29. Yu, C., Zhong, W., Estey, B., et al. 2019, Atom-interferometry measurement of the fine structure constant. *Ann. Physik*, **531**, 1800346
30. Workman, R. L., Burkert, V. D., Crede, V., et al. 2022, Review of particle physics. *Prog. Theor. Exp. Phys.*, **2022**(8), 083C01
31. Navas, S., Amsler, C., Gutsche, T. et al. 2024, Review of particle physics. *Phys. Rev. D*, **110**, 030001
32. Christodoulou, D. M., & Kazanas, D. 2024, Introducing the effective gravitational constant  $4\pi\epsilon_0 G$ . *Preprints*, 2024110749. <https://doi.org/10.20944/preprints202411.0749.v3> (accessed on 26 August 2025)
33. Milgrom, M. 2014, MOND laws of galactic dynamics. *Mon. Not. R. Astron. Soc.*, **437**, 2531
34. Milgrom, M. 2015, MOND theory. *Can. J. Phys.*, **93**, 107
35. Christodoulou, D. M., & Kazanas, D. 2023, Varying-G gravity. *Mon. Not. R. Astron. Soc.*, **519**, 1277
36. Christodoulou, D. M., O'Leary, J., Melatos, A., Kimpson, T., Bhattacharya, S., O'Neill, N. J., Laycock, S. G. T., & Kazanas, D. 2025, Magellanic accretion-powered pulsars studied via an unscented Kalman filter. *Astrophys. J.*, **988**, 275
37. Wikipedia 2025g, Black hole electron. Online at [https://en.wikipedia.org/wiki/Black\\_hole\\_electron](https://en.wikipedia.org/wiki/Black_hole_electron) (accessed on 29 August 2025)
38. Wikipedia 2025h, Extremal black hole. Online at [https://en.wikipedia.org/wiki/Extremal\\_black\\_hole](https://en.wikipedia.org/wiki/Extremal_black_hole) (accessed on 25 August 2025)

39. Majumdar, S. D. 1947, A class of exact solutions of Einstein's field equations. *Phys. Rev.*, **72**, 390
40. Papapetrou, A. 1947, A static solution of the equations of the gravitational field for an arbitrary charge-distribution. *Proc. Roy. Irish Acad. 1945-1948*, **A51**, 191
41. Israel, W., & Wilson, G. A. 1972, A class of stationary electromagnetic vacuum fields. *J. Math. Phys.*, **13**, 865
42. Hartle, J. B., & Hawking, S. W. 1972, Solutions of the Einstein-Maxwell equations with many black holes. *Commun. Math. Phys.*, **26**, 87
43. Heusler, M. 1997, On the uniqueness of the Papapetrou-Majumdar metric. *Class. Quantum Grav.*, **14**, L129
44. Albacete, E., & Richartz, M. 2024, Tidal forces in Majumdar-Papapetrou spacetimes. *Universe*, **10**, 62
45. Carter, B. 1968, Global structure of the Kerr family of gravitational fields. *Phys. Rev.*, **174**, 1559
46. Misner, C. W., Thorne, K. S., & Wheeler, J. A. *Gravitation*; W. H. Freeman & Company: San Francisco, CA, USA, 1973; pp. 920-921
47. Li, Q., Xue, C., Liu, J.-P., Wu, J.-F. 2018, Measurements of the gravitational constant using two independent methods. *Nature*, **560**, 582
48. Xue, C., Liu, J.-P., Li, Q., Wu, J.-F., et al. 2020, Precision measurement of the Newtonian gravitational constant. *National Science Review*, **7**, 1803
49. Christodoulou, D. M., & Kazanas, D. 2018, Interposing a varying gravitational constant between modified Newtonian dynamics and weak Weyl gravity. *Mon. Not. R. Astron. Soc.*, **479**, L143
50. Tohline, J. E. Stabilizing a cold disk with a  $1/r$  force law. In: Athanassoula, E. (ed.) *Internal Kinematics and Dynamics of Galaxies*, IAU Symposia, Vol. 100, Springer: Dordrecht, Germany, 1983; p. 205
51. Tohline, J. E. 1984, Does gravity exhibit a  $1/r$  force on the scale of galaxies?. *Ann. NY Acad. Science*, **422**, 390
52. Kuhn, J. R., & Kruglyak, L. 1987, Non-Newtonian forces and the invisible mass problem, *Astrophys. J.*, **313**, 1
53. Feynman, R. P. *QED: The strange theory of light and matter*; Princeton University Press: Princeton, USA, 1985; p. 128
54. Miller, A. I. 137: *Jung, Pauli, and the pursuit of a scientific obsession*; W. W. Norton & Company, New York, USA, 2009
55. CDF Collaboration, Aaltonen, T., Amerio, S., Amidei, D., et al. 2022, High-precision measurement of the  $W$  boson mass with the CDF II detector. *Science*, **376**, 170
56. Rohlf, J. W. 1994, *Modern Physics*; John Wiley & Sons: New York, USA; p. 26
57. Lee, T. D. 2004, *Particle Physics and Introduction to Field Theory*; Taylor & Francis: Boca Raton, USA; pp. 671-686
58. Peskin, M. E., & Schroeder, D. V. 1995, *An Introduction to Quantum Field Theory*; CRC Press: Boca Raton, USA; pp. 184-196, 702-703
59. Landé, A. 1921, Ueber den anomalen Zeemaneffekt (Teil I). *Z. Physik*, **5**, 231
60. Schwinger, J. 1948, On quantum-electrodynamics and the magnetic moment of the electron. *Phys. Rev.*, **73**, 416
61. Dirac, P. A. M. 1928, The quantum theory of the electron. *Proc. R. Soc. Lond. A*, **117**, 610
62. Bekenstein, J. D. 1972, Black holes and the second law. *Lett. Nuovo Cimento*, **4**, 737
63. Hawking, S. W. 1975, Particle creation by black holes. *Commun. Math. Phys.*, **43**, 199
64. Carlip, S. 2014, Black hole thermodynamics. *Int. J. Mod. Phys. D*, **23**, 1430023
65. Bekenstein, J. D. 1981, Universal upper bound on the entropy-to-energy ratio for bounded systems. *Phys. Rev. D*, **23**, 287
66. Bousso, R. 2004, Bound states and the Bekenstein bound. *J. High Ener. Phys.*, **2004(2)**, 025
67. Bekenstein, J. D. 2005, How does the entropy/information bound work? *Found. Phys.*, **35**, 1805
68. Tipler, F. J. 2005, The structure of the world from pure numbers. *Rep. Prog. Phys.*, **68**, 897
69. Casini, H. 2008, Relative entropy and the Bekenstein bound. *Class. Quantum Grav.*, **25**, 205021
70. Hawking, S. W. 1974, Black hole explosions? *Nature*, **248**, 30
71. Davies, P. C. W. 1975, Scalar production in Schwarzschild and Rindler metrics. *J. Phys. A: Math. Gen.*, **8**, 609
72. Unruh, W. G. 1976, Notes on black-hole evaporation. *Phys. Rev. D*, **14**, 870
73. Alsing, P. M., & Milonni, P. W. 2004, Simplified derivation of the Hawking-Unruh temperature for an accelerated observer in vacuum. *Am. J. Phys.*, **72**, 1524
74. Gibbons, G. W. 2002, The maximum tension principle in general relativity. *Found. Phys.*, **32**, 1891
75. Barrow, J. D., & Gibbons, G. W. 2015, Maximum tension: with and without a cosmological constant. *Mon. Not. R. Astr. Soc.*, **446**, 3874
76. Barrow, J. D., & Gibbons, G. W. 2017, Maximum magnetic moment to angular momentum conjecture. *Phys. Rev. D*, **95**, 064040
77. Barrow, J. D., & Dadhich, N. 2020, Maximum force in modified gravity theories. *Phys. Rev. D*, **102**, 064018

78. Heisenberg, W. 1927, Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik. *Z. Physik*, **43**, 172
79. Kennard, E. H. 1927, Zur Quantenmechanik einfacher Bewegungstypen. *Z. Physik*, **44**, 326
80. Weyl, H. *Gruppentheorie und Quantenmechanik*; S. Hirzel: Leipzig, Germany, 1928
81. Balanis, C. A. 2005, *Antenna theory*; John Wiley & Sons, Hoboken, p. 159
82. Casimir, H. B. G. 1948, On the attraction between two perfectly conducting plates. *Proc. Kon. Ned. Akad. Wet.*, **51**, 793
83. Schwinger, J. 1975, Casimir effect in source theory. *Lett. Math. Phys.*, **1**, 43
84. Schwinger, J. 1992, Casimir effect in source theory II. *Lett. Math. Phys.*, **24**, 59
85. Zee, A. *Quantum field theory in a nutshell*; Princeton University Press: Princeton, NJ, USA, 2003, p. 66
86. Jaffe, R. L. 2005, The Casimir effect and the quantum vacuum. *Phys. Rev. D*, **72**, 021301
87. Decca, R. S., López, D., Fischbach, E., Klimchitskaya, G. L., Krause, D. E., & Mostepanenko, V. M. 2007, Tests of new physics from precise measurements of the Casimir pressure between two gold-coated plates. *Phys. Rev. D*, **75**, 077101
88. Liu, M., Xu, J., Klimchitskaya, G. L., Mostepanenko, V. M., & Mohideen, U. 2019, Precision measurements of the gradient of the Casimir force between ultraclean metallic surfaces at larger separations. *Phys. Rev. A*, **100**, 052511
89. de Jong, M. H., Korkmazgil, E., Banniard, L., Sillanpää, M. A., & de Lépinay, L. M. 2025, Measurement of the Casimir force between superconductors. *arXiv*, 2501.13759, Online at <https://doi.org/10.48550/arXiv.2501.13759> (accessed on 7 May 2025)
90. Nikolić, H. 2016, Proof that Casimir force does not originate from vacuum energy. *Phys. Lett. B*, **761**, 197
91. Nikolić, H. 2017, Is zero-point energy physical? A toy model for Casimir-like effect. *Ann. Phys.*, **383**, 181
92. Dzyaloshinskii, I. E., Lifshitz, E. M., & Pitaevskii, L. P. 1961, General theory of van der Waals forces. *Sov. Phys. Usp.*, **4**, 153
93. Dzyaloshinskii, I. E., & Kats, E. I. 2004, Casimir forces in modulated systems. *J. Phys: Condens. Matter*, **16**, 5659
94. Rodriguez, A. W., Capasso, F., & Johnson, S. G. 2011, The Casimir effect in microstructured geometries. *Nature Photonics*, **5**, 211
95. Casimir, H. B. G., & Polder, D. 1948, The influence of retardation on the London-van der Waals forces. *Phys. Rev.*, **73**, 360
96. Parsegian, V. A. *Van der Waals forces*; Cambridge University Press: Cambridge, UK, 2006
97. Christodoulou, D. M., Kazanas, D., & Laycock, S. G. T. 2025, The gravitational force on charges and the electric force on masses, two extremely weak action-reaction pairs, and the geometric-mean relations of the fundamental constants of nature. *Preprints*, 2025031630. <https://doi.org/10.20944/preprints202503.1630.v1> (accessed on 28 August 2025)
98. Milgrom, M. 1983a, A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis. *Astrophys. J.*, **270**, 365
99. Milgrom, M. 1983b, A modification of the Newtonian dynamics – Implications for galaxies. *Astrophys. J.*, **270**, 371
100. Milgrom, M. 1983c, A modification of the Newtonian dynamics: Implications for galaxy systems. *Astrophys. J.*, **270**, 384
101. Famaey, B., & McGaugh, S. S. 2012, Modified Newtonian Dynamics (MOND): Observational phenomenology and relativistic extensions. *Living Rev. Rel.*, **15**, 10
102. Christodoulou, D. M., & Kazanas, D. 2019, Gauss's law and the source for Poisson's equation in modified gravity with varying  $G$ . *Mon. Not. R. Astron. Soc.*, **484**, 1421
103. Tully, R. B., & Fisher, J. R. 1977, A new method of determining distances to galaxies. *Astron. Astrophys.*, **54**, 661
104. McGaugh, S. S., Schombert, J. M., Bothun, G. D., & de Blok, W. J. G. 2000, The baryonic Tully-Fisher relation. *Astrophys. J.*, **533**, L99
105. McGaugh, S. S. 2012, The baryonic Tully-Fisher relation of gas-rich galaxies as a test of  $\Lambda$ CDM and MOND. *Astron. J.*, **143**, 40
106. Faber, S. M., & Jackson, R. E. 1976, Velocity dispersions and mass-to-light ratios for elliptical galaxies. *Astrophys. J.*, **204**, 668
107. Sanders, R. H. 2009, Modified Newtonian Dynamics: A falsification of cold dark matter. *Adv. in Astron.*, **2009**, 752439

108. den Heijer, M., Oosterloo, T. A., Serra, P., et al. 2015, The HI Tully-Fisher relation of early-type galaxies. *Astron. Astrophys.*, **581**, A98
109. McGaugh, S. S., Lelli, F., & Schombert, J. M. 2016, Radial acceleration relation in rotationally supported galaxies. *Phys. Rev. Lett.*, **117**, 201101
110. Lelli, F., McGaugh, S. S., Schombert, J. M., & Pawlowski, M. S. 2017, One law to rule them all: The radial acceleration relation of galaxies. *Astrophys. J.*, **836**, 152
111. Wutke, A. 2023, From Newton to universal Planck natural units – disentangling the constants of nature. *J. Phys. Commun.*, **7**, 115001
112. Dimopoulos, S., Raby, S. A., & Wilczek, F. 1991, Unification of couplings. *Physics Today*, **44**, 25
113. Wilczek, F. 2016, Theory Vision, LHCP 2016. *PoS (LHCP2016)*, **276**, 47
114. Good, I. J. A quantal hypothesis for hadrons and the judging of physical numerology. In: G. R. Grimmett and D. J. A. Welsh (eds.) *Disorder in Physical Systems*; Oxford University Press: New York, NY, USA, 1990; p. 141
115. MIT OpenCourseWare 2001, 18.013A Calculus with Applications, Fall 2001: Chapter 28.1 – Electricity and Magnetism. Massachusetts Institute of Technology, online at <https://ocw.mit.edu/ans7870/18/18.013a/textbook/chapter28/section01.html> (accessed on 12 September 2025)
116. The Telescope Array Collaboration, 2018, The cosmic ray energy spectrum between 2 PeV and 2 EeV observed with the TALE detector in monocular mode. *Astrophys. J.*, **865**, 74
117. Di Sciascio, G. 2022, Measurement of energy spectrum and elemental composition of PeV cosmic rays: Open problems and prospects. *Appl. Sci.*, **12**, 705
118. Kang, D., & Haungs, A. 2024, The cosmic-ray spectrum in the PeV to EeV energy range. *Adv. Space Res.*, **74**, 4403
119. The KM3NeT Collaboration, 2025, Observation of an ultra-high-energy cosmic neutrino with KM3NeT. *Nature*, **638**, 376
120. The IceCube Collaboration, 2025, Search for extremely-high-energy neutrinos and first constraints on the ultrahigh-energy cosmic-ray proton fraction with IceCube. *Phys. Rev. Lett.*, **135**, 031001

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.