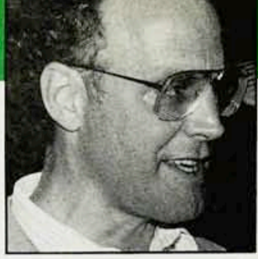


CAN WE SCALE THE PLANCK SCALE?

David J. Gross

In May 1899 Max Planck published his first paper on the spectrum of blackbody radiation. In this paper he introduced for the first time the constant h, later to be understood as the quantum of action, which bears his name. Planck is very excited in this paper, but his excitement is not (as you might have thought) about the introduction of quantization or the overthrow of classical physics. He is not yet aware of these revolutionary implications of his discovery. Rather he is excited about the appearance in his law of a dimensional constant of action, which together with the other fundamental constants, the velocity of light c and Newton's gravitational constant G, completes the trio of fundamental units.

He states that the existence of this fundamental constant of nature "offers the possibility of establishing units for length, mass and time which are independent of specific bodies and which maintain their meaning for all time and for all civilizations, even those which are extraterrestrial and nonhuman; constants which therefore can be called 'fundamental units of measurement.'" Indeed, if we were to communicate with a civilization of Sirius, one surefire way of comparing the scale of our rulers and watches would be to use the fundamental units named in honor of Planck. These are the Planck length

$$L_{\text{Planck}} = (Gh/c^3)^{1/2} \approx 10^{-33}\ \text{cm}$$

the Planck time

$$T_{\text{Planck}} = (G/c^5)^{1/2} \approx 10^{-43}\ \text{sec}$$

and the Planck mass

$$M_{\text{Planck}} = (hc/G)^{1/2} \approx 10^{-5}\ \text{gram}$$

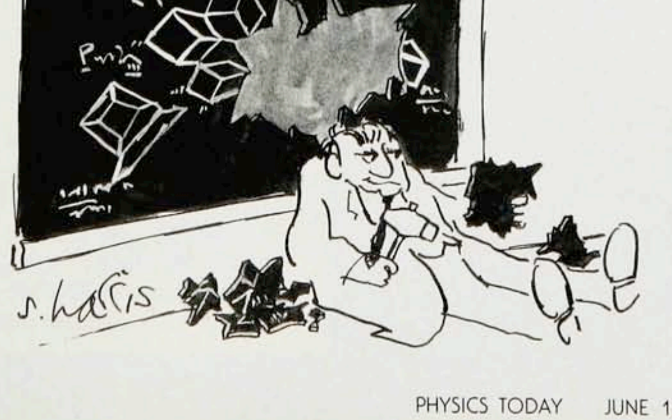
What is so striking about these fundamental units is that their sizes are so incredibly disparate. We are accustomed to the extraordinarily small size of the atom and the nucleus, but the Planck length is removed from these by 20 to 26 orders of magnitude. The Planck time is as short compared with times for atomic phenomena as the latter are compared with the age of the universe. The Planck mass might appear to be of reasonable size until we remember that the mass of a typical elementary particle, such as the proton, is only 10^{-24} gram, 10^{19} times smaller.

The enormous disparity between these scales and the atomic and nuclear scales is one of the most remarkable facts of nature. Theorists attempting to bridge these scales find it difficult to explain a number as large as 10^{19} and call this the hierarchy problem. Although a problem for theorists, the hierarchy is responsible for some of the most welcome features of our universe.

The most important practical consequence of the hierarchy is the weakness of gravity at large scales. The gravitational force between two protons in a nucleus is approximately $(M_{\text{proton}}/M_{\text{Planck}})^2 \approx 10^{-38}$ of the strong nuclear force that acts between them. This is why gravitational forces can be safely ignored in the laboratory. The only time gravity becomes noticeable is when we gather together many, many protons. Since the gravitational force is additive, once we put together 10^{40} protons, as in a small planet, we get a reasonable force.

The hierarchy is also responsible for the fact that stars, planets and people are made out of so many atoms. The maximum size of stars is controlled by the strength of gravity, which causes stars of overly large mass to collapse. Based on S. Chandrasekhar's discussion of stellar collapse, the maximum number of protons in a star is essentially of order $(M_{\text{Planck}}/M_{\text{proton}})^3 \approx 10^{57}$. We can therefore thank the hierarchy for the complexity and diversity of our world.

How can we ever hope to understand these incredibly large numbers? Paul Dirac, the first to tackle this issue seriously, suggested that the large numbers associated with the hierarchy are related to other large numbers in the universe—the age of the universe in atomic units and the number of protons in the observable universe. Since these quantities



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change with time, he predicted that the gravitational constant G should be time dependent. This idea has not been totally ruled out, but the associated prediction in unified theories that the fine-structure constant varies on cosmological time scales contradicts observation.

Modern attempts to explain the hierarchy invoke two mechanisms. First, the slow logarithmic increase of non-Abelian gauge forces with decreasing energy suggests that if these forces are weak at the Planck scale, they will be of reasonable strength for energies 17 orders of magnitude lower. At this lower-energy scale they could cause the electroweak symmetry breaking that generates the W mass, as well as produce the dynamics of quark confinement that determines the proton mass. The second mechanism required to make this scenario work is necessary to prevent the scalar Higgs particles from developing Planck-size masses. This can be done if one invokes supersymmetry, a beautiful extension of ordinary space–time symmetries. In fact, the main phenomenological reason for believing in supersymmetry is to explain the hierarchy.

Confronting the hierarchy is at the heart of recent efforts to unify the forces of nature. Straightforward attempts to extrapolate the extremely successful standard model of the electroweak and strong interactions to higher energies point to the Planck regime as the place where fundamentally new physics and further unification will emerge. At such very high energies gravity becomes a strong force, because its strength depends on distance and energy. According to Newton, the gravitational attraction between two bodies is proportional to the product of their masses. In a relativistic theory mass is replaced by energy and so the force of gravity increases with energy. At the natural scale of the world, the Planck scale, gravity has the same strength as the other forces of nature and is presumably combined with them into a unified theory.

Recently there have been ambitious and very promising efforts in the direction of unification, most notably in string theory. Critics of string theory have argued that any attempt to reach the Planck scale, removed by 17 orders of magnitude from current experiments, is foolhardy and doomed to failure. In a subsequent column I hope to respond to the critics of string theory. I believe that we have no choice. We must attempt to explore Planckian physics, whatever the difficulties. ■