

Peter J. Riggs*

The Physical State of the Universe in the Planck Era

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Abstract: The Planck Era cannot be given an accurate mathematical description until the full theory of quantum gravity is available. However, some aspects of the physical state of the Planck Era can be revealed by order of the magnitude considerations which also have implications for the low entropy of the very early universe.

Keywords: Early Universe; Low Entropy; Planck Era.

1 Introduction

In expanding cosmological models, a global cosmic time (t) is defined as the relativistic proper time at each cluster of galaxies, i.e. the time that would be measured by a clock sharing the average motion of matter in the universe [1]. The zero of cosmic time is commonly referred to as the Big Bang. The Planck Era of the universe is an ultra-short time period immediately after the Big Bang [2]. In this era, general relativity does not provide an adequate physical account. The (as yet unavailable) full, i.e. mathematically consistent and empirically confirmed, theory of quantum gravity is needed to provide a quantitative description [3, 4]. It is widely accepted that the very early universe had low total entropy in comparison with today [5–8]. The low entropy assumption is viable in that we observe that the entropy of the universe was lower in the past [9] and that this situation seems necessary to account for the operation of the Second Law of Thermodynamics [6, 10]. The aim of this article is to show what some straight-forward dimensional and order of magnitude considerations can reveal about the universe's physical state during the Planck Era and its implications for the entropy of the universe.

2 The Planck Era

The Planck Era spans the cosmic time interval: $0 < t \leq t_p$, where t_p is called the Planck time. On a dimensional basis,

*Corresponding author: Peter J. Riggs, Department of Quantum Science, Australian National University, Building 38a, Science Road, Canberra ACT 2601, Australia, E-mail: peter.riggs@anu.edu.au

the Planck time is obtained from combining the fundamental constants of universal gravitation (G), the speed of light in vacuum (c) and the Planck's constant divided by 2π ($\hbar$), i.e. $t_p = (\hbar G/c^5)^{1/2}$. These constants, respectively, set the scales at which gravitational, relativistic and quantum effects become significant [11]. The combination of these fundamental constants (especially incorporating quantum effects through $\hbar$) to produce a calculable time demonstrates the validity of the time interval of the Planck Era. In other words, even in the absence of a full theory of quantum gravity, it is still possible to offer a well-grounded definition of the Planck Era's cosmic time interval. The numerical value of t_p ($\approx 10^{-43}$ s) is taken as the smallest physically meaningful quantity with respect to time [12, 13].

The Planck Era had a physical state of unimaginatively severe conditions with a temperature calculated in excess of 10^{32} K [14]. As a complete mathematical account of its physical state is not yet formulated, the quantitative predictions of existing approaches to quantum gravity cannot be relied upon. Indeed, the absence of a full theory of quantum gravity has led to claims that any statement about the Planck Era is pure speculation. These claims are not strictly correct for approximate quantities may be calculated, e.g. temperature. It is also possible to reach some general results with respect to the Planck Era. General results may be arrived at by using heuristic arguments as such arguments are sufficient to show generic consequences even before precise predictions are possible [15]. Any findings about the Planck Era need to be restricted to (at most) order of magnitude and/or qualitative results.

3 Expansion of the Universe and its Entropy

Given that the Planck time unit is the smallest meaningful time quantity, physical processes would not progress within one such individual time unit as this would imply a smaller time unit is physically meaningful. Consequently, the expansion of the universe would have begun only after the Planck Era. The distance corresponding to one Planck time unit is the Planck length $l_p = (\hbar G/c^3)^{1/2} \approx 10^{-33}$ cm, which also is taken as the smallest physically meaningful quantity with respect to length [16, 17]. Regardless of

whether the universe is spatially infinite or not, we need to focus attention to the finite region of space that today is the observable universe, which will be denoted as the causal region. This is the space within the observable universe's particle horizon. The horizon 'radius' would be of the order of l_p in the Planck Era [18, 19].

Based on the miniscule temperature variation of the cosmic microwave background (CMB), the very early universe was in thermal equilibrium. The entropy can be determined from the CMB to have a value of about 10^{88} in natural units [20, 21], i.e. units in which Boltzmann's constant $k_B = 1$. This CMB entropy value has essentially remained the same since the universe began expanding [22]. However, the entropy of the observable universe is dominated by supermassive black holes and is estimated at 10^{104} in natural units [23]. Obviously, the CMB entropy is low in comparison to the observable universe's entropy. The entropy increase of 16 orders of magnitude over the universe's lifetime was explained by cosmic inflation theory [24, 25]. Why is the CMB entropy value so low? In order to address this issue, gravitational entropy needs to be considered.

It is recognised that gravitational entropy behaves differently to what would be expected from thermodynamic entropy as the former increases as matter gets closer to the other matter [26–28]. Nevertheless, although a general expression for gravitational entropy is not yet derived [29], the entropy S_{BH} of a black hole may be found from the Bekenstein–Hawking equation [30]:

$$S_{BH} = k_B c^3 A / 4G\hbar \quad (1)$$

where A is the surface area of the black hole's event horizon. Equation (1) also gives the maximum possible entropy for any region of space of the same area A [31, 32]. In the case of a spherical, non-rotating Schwarzschild black hole, the entropy S_{SBH} is given by:

$$S_{SBH} = k_B \pi GM^2 / \hbar c \quad (2)$$

where M is the mass equivalent to the energy contained in the black hole [33]. We can partially model the state of the observable universe as a Schwarzschild black hole where M corresponds to the total mass for the estimated number of baryons (10^{80}). Then the entropy obtained using (2) is approximately 10^{122} in natural units [34] and is obviously greater than the estimated entropy of the observable universe (10^{104}) by 18 orders of magnitude. However, the figure 10^{122} represents the maximum entropy for any (spherical) region of space containing the same mass bounded by the same area (and therefore same volume) as a black hole's event horizon.

Penrose has questioned why the observable universe's entropy is so much lower than this maximal possible amount [35] as a smaller difference would still allow for the operation of the Second Law. Penrose suggested a geometrical explanation in which gravitational entropy is taken into account. He associates the Weyl curvature tensor in general relativity with gravitational entropy such that the value of Weyl curvature is zero (or at least very small) close to the Big Bang [36]. An initial condition of the universe which specifies that its matter distribution be isotropic and homogeneous would need to be postulated to achieve the result of a zero (or very small) Weyl curvature [37].

4 Matter at Ultra-Extreme Temperatures

The terms 'matter' and 'anti-matter', for current purposes, are used to describe anything with mass irrespective of their energies. It is empirically confirmed that matter progressively disintegrates at higher and higher temperatures, e.g. molecules dissociate to atoms and atoms to nucleons. At energies (and hence temperatures) only just starting to be achieved with particle accelerators, nucleons break down (at about 10^{12} K) to quarks and gluons, the so-called 'quark soup', which are free to move independently [38].

What would happen to matter at temperatures significantly higher than 10^{12} K? Currently confirmed elementary particle theory does not provide a definite answer [39, 40]. Nevertheless, although little is expected to occur for many e-foldings of temperature above 10^{12} K [41], it would be physically unjustifiable to assume that quarks and gluons will remain intact irrespective of how large a temperature is reached. If quark soup was unchanged regardless of temperature then matter would be essentially indestructible, contrary to observation. Particle-antiparticle annihilation clearly shows that matter is not indestructible [42]. The progressive breakdown of matter as temperature increases together with the process of annihilation suggests that at temperatures and energies substantially greater than those achievable with particle accelerators, matter would cease to exist.

What then would result from matter being raised to ultra-extreme temperatures (i.e. energies $\gg 10^{12} k_B$)? Supersymmetric and other current theories that go beyond the standard model of elementary particles do not offer plausible answers as there are robust empirical reasons for not accepting these theories. The principal reasons for their

non-acceptance are: (i) continued experimental confirmation of the standard model; and (ii) failure to find any data in support of supersymmetry or extra spatial dimensions [43–45]. In the absence of guidance from the standard model, it is reasonable to conclude that what would result at ultra-extreme temperatures is the same as what matter will ‘decay’ to the given enough time, as it is well established that significant rises in temperature accelerate decaying processes. It is plausibly argued elsewhere that electromagnetic radiation, i.e. (massless) photons, is matter’s ultimate fate [46–48]. Then electromagnetic radiation should also be expected to be the end result of raising quark soup to ultra-extreme temperatures. Hence, only electromagnetic radiation should exist at temperatures far beyond 10^{12} K. This inference may be applied to assist in understanding the physical state of the universe during the Planck Era.

5 The Universe’s Physical State in the Planck Era

As distances less than l_p cannot be entertained as physically meaningful, the universe (or at least the causal region) had a radius of l_p throughout the Planck Era and, as already noted, its expansion would not have started for (at least) a time interval t_p after the Big Bang. This raises a problem for the existence of particles of finite size during the Planck Era. If particles are taken as point entities then the problem is avoided but realistically, all matter and anti-matter particles will have some size. Fundamental particles, e.g. quarks, have a size of order 10^{-17} cm $\gg l_p$ [49]. Such fundamental particles would not fit in a (finite) Planck Era sized universe (or in the causal region) [50].

We can model the universe during the Planck Era as a Schwarzschild black hole [51] when the Schwarzschild radius equals the Planck length. Then, from (1) and the definition of the Planck length, we have the entropy of the Planck Era S_{PE} as:

$$S_{PE} = k_B c^3 \pi l_p^2 / G \hbar = \pi k_B \quad (3)$$

which is of order one in natural units. However, the question that immediately arises is whether (3) holds in the Planck Era because classical relations can be expected to break down as the Planck scale is approached. Quantum mechanics requires that when both the Schwarzschild radius and the corresponding Compton wavelength are approximately equal to the Planck length, then quantum effects dominate [52]. As the Compton wavelength is the

minimum distance of localisation, the ‘black hole radius’ will have an uncertainty of the same size as the radius, i.e. of order l_p [53, 54]. Recall that any numerical findings about the Planck Era are restricted to order of magnitude estimates as quantitative results from existing quantum gravity approaches are excluded. Based on this, the order of magnitude estimate for entropy in the Planck Era would remain at order one in natural units (as the possible entropy value would only increase by a factor of four). As the causal region radius cannot be smaller than l_p in the Planck Era, the entropy value will be at a maximum (of order one in natural units). Therefore, there was no change in entropy during the Planck Era.

It is already mentioned that, in the Planck Era, temperature was 20 orders of magnitude above quark soup and that there is a size problem for fundamental particles. These considerations combined with the entropy value being at a maximum signify that the Planck Era conditions were completely unsuitable for the existence of any particles (or anti-particles) and consequently, the universe was devoid of matter and anti-matter during the Planck Era. Note that the use of (3) does not require the universe to contain particles/anti-particles during the Planck Era.

Despite there being more than sufficient energy to create particle-antiparticle pairs, matter and anti-matter were absent from the universe in the Planck Era as these creation processes require a massive increase in entropy and the size of the causal region to be larger by many orders of magnitude. The formation of particle-antiparticle pairs then would only have begun once the universe expanded in size and its temperature dropped. Some estimates indicate that particle creation probably occurred at about 10^{-30} s [55]. The maximum entropy at this time was approximately 10^{74} (which is much greater than the maximum Planck Era entropy) and the radius of the causal region $\approx 10^4$ cm. This conclusion solves the fundamental particle size problem.

If there were no particles of matter (or anti-matter) during the Planck Era then the universe was a vacuum throughout this time period. The limits on what may be concluded about the Planck Era restricts what can be claimed about the properties of this vacuum other than it contained physical fields. It is acknowledged that the initial state of the universe being a vacuum was previously suggested [56] but was based on different reasons from those given above. Importantly, the universe being a vacuum in the Planck Era shows that its entropy could neither depend on the quantity of matter nor on the distribution of matter (as none existed at that time). The entropy of the Planck Era would have only geometrical and electromagnetic origins which greatly reduce the

number of accessible physical states for the universe. As entropy is a measure of the number of accessible states [57], the entropy of the universe would have had a smaller value than would be the case if the initial state of the universe was not a vacuum. It is not necessary then to postulate an initial condition of the universe requiring matter distribution to be isotropic and homogeneous if the initial state was a vacuum.

6 Conclusions

In spite of not having a full theory of quantum gravity, it is possible to arrive at some qualitative and order of magnitude results about the physical state of the universe in the Planck Era. In particular:

- (i) the size of the causal region of the universe was of order l_p ;
- (ii) the observable universe had a maximum entropy value;
- (iii) the universe was devoid of matter/anti-matter;
- (iv) the absence of matter/anti-matter greatly reduced the number of accessible physical states for the universe at that time; and
- (v) this reduced number of accessible states (in part) accounts for the Planck Era's very low entropy in comparison with the value found today.

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