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On the physical basis of cosmic time

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ABSTRACT

In this manuscript we initiate a systematic examination of the physical basis for the time concept in cosmology. We discuss and defend the idea that the physical basis of the time concept is necessarily related to physical processes which could conceivably take place among the material constituents available in the universe. As a consequence we motivate the idea that one cannot, in a well-defined manner, speak about time 'before' such physical processes were possible, and in particular, the idea that one cannot speak about a time *scale* 'before' scale-setting physical processes were possible. It is common practice to link the concept of cosmic time with a space–time metric set up to describe the universe at large scales, and then define a cosmic time t as what is measured by a comoving standard clock. We want to examine, however, the physical basis for setting up a comoving reference frame and, in particular, what could be meant by a standard clock. For this purpose we introduce the concept of a 'core' of a clock (which, for a standard clock in cosmology, is a scale-setting physical process) and we ask if such a core can—in principle—be found in the available physics contemplated in the various 'stages' of the early universe. We find that a first problem arises above the quark–gluon phase transition (which roughly occurs when the cosmological model is extrapolated back to $\sim 10^{-5}$ s) where there might be no bound systems left, and the concept of a physical length scale to a certain extent disappears. A more serious problem appears above the electroweak phase transition believed to occur at $\sim 10^{-11}$ s. At this point the property of mass (almost) disappears and it becomes difficult to identify a physical basis for concepts like length scale, energy scale and temperature—which are all intimately linked to the concept of time in modern cosmology. This situation suggests that the concept of a time scale in 'very early' universe cosmology lacks a physical basis or, at least, that the time scale will have to be based on speculative new physics.

1. Introduction

Most cosmologists would agree that the physics describing the 'material content' of the universe becomes increasingly speculative the further we go back in time. By contrast, it is widely assumed that the concept of time (and space) itself—by virtue of a cosmological space–time metric—can be safely extrapolated 60 orders of magnitude back from the present to the Planck scales. Apart from some interesting hints in Misner, Thorne, and Wheeler (1973) (see also Misner, 1969), we have found no discussions in cosmology which address the issue of whether time, like the physical description of the material content, could become more and more speculative as we go back in 'time'. Studies addressing the time concept at the Planck scale are of course abundant, cf. the problem of time in quantum gravity and quantum cosmology. But what we want to question here is whether the time concept is well-defined as a physical concept in cosmology 'before' (in the backward extrapolation from the present) the Planck scale is reached. The guiding question is thus: How far back in time can we go while maintaining a well-defined time concept?

It is standard to assume that a number of important events took place in the first tiny fractions of a second 'after' the big bang. For instance, the universe is thought to have been in a quark–gluon phase between 10^{-11} and 10^{-5} s, whereas the fundamental material constituents are massless (due to the electroweak (Higgs) transition) at times earlier than $\sim 10^{-11}$ s. A phase of inflation is envisaged (in some models) to have taken place around 10^{-34} s after the big bang. A rough summary of the phases of the early universe is given in Fig. 1.

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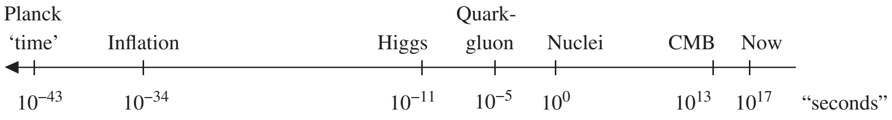

Fig. 1. Contemplated phases of the early universe.

While the various phases indicated in Fig. 1 will be discussed in some detail in the present manuscript, a few comments and clarifications should be made here:

(i) The figure is to scale, that is, it captures e.g. that it is (logarithmically) *shorter* from the present back to the Higgs transition—which more or less indicates the current limit of known physics (as explored in Earth-based experiments)—than from the Higgs transition back to the Planck time located at $(\hbar G/c^5)^{1/2}\sim 10^{-43}$ s. This illustrates just how far extrapolations extend in modern cosmology![1]

(ii) Whereas one usually speaks of time elapsed *since* the big bang, the observational point of departure is the present—hence the direction of the arrow (we extrapolate backwards from now). For lack of viable alternatives, however, we shall in the following use the standard time indications from the big bang (we shall thus also speak about 'seconds after the BB').

(iii) The quotation marks around seconds are included since, as we shall discuss, it is far from straightforward that one can 'carry back' this physical scale as far as one would like.

An objection to the study we propose might be that if time is well-defined within the Friedmann–Lemaître–Robertson–Walker (FLRW) metric, standardly taken to describe the present universe (at large scales), there seems to be no problem in extrapolating this time concept back to $t = 0$ or, at least, to the Planck time. However, this objection disregards that the FLRW metric is a mathematical model containing a parameter t which is *interpreted* as time. Whereas, as a mathematical study, one may consider arbitrary small values of t, our aim here is precisely to investigate under what conditions—and in which t-parameter range—one is justified in making the interpretation

$t \leftrightarrow$ time.

In this paper we shall motivate and discuss the suggestion that a physical condition for making the $t\leftrightarrow$ time interpretation in cosmology is the (at least possible) existence of a physical process which can function as what we call the 'core' of a clock. In particular, we suggest that in order to make the $t\leftrightarrow$ time interpretation at a specific cosmological 'epoch', the physical process acting as the core of a clock should (1) have a well-defined duration which is sufficiently fine-grained to 'time' the epoch in question; and (2) be a process which could conceivably take place among the material constituents available in the universe at this epoch. Consequently, we shall devote a large part of the investigation to an examination of what such a core of a clock could be in the context of early universe cosmology. Our analysis suggests that the physical basis of time—or, more precisely, the time scale—becomes rather uncertain already when the FLRW metric is extrapolated back to $\sim 10^{-11}$ s. This could indicate that the time scale concept becomes insufficiently founded (or at least highly speculative) already ~30 orders of magnitude 'before' the Planck time is reached.

Our reasoning is based on the observation that we shall be (almost) unable to find scale-setting physical processes (cores of clocks) in the 'desert' above the Higgs phase transition—if the physics is based on an extrapolation of what is considered well-known and established physics in the form of the standard model of the electroweak and strong forces. In order to provide a physical foundation for the time scale above the Higgs transition we will have to base it on speculative new physics, and the time scale linked to this new physics will be speculative as well. Moreover, the in-principle existence of extended physical objects which can function as rods (which appear to be a prerequisite to set up the coordinate frame in cosmology, see Section 3) becomes gradually less clear: above the quark–hadron phase transition (at $t\sim 10^{-5}$ s) there are roughly no bound systems left, and the notion of length and time scales becomes even more ill-defined above the Higgs phase transition (at $t\sim 10^{-11}$ s) if those scales are to be constructed out of the by-then available massless material constituents.

The structure of the paper is as follows. In Section 2 we discuss the meaning of time, and suggest that the well-defined use of time in both ordinary practical language and physics is necessarily related to the notion of a physical process which can function as a clock or a core of a clock. In Section 3 we briefly investigate the time and clock concepts as they are employed in cosmology and the underlying theories of relativity.[2] In Section 4 we examine the possible physical underpinnings for (cores of) clocks in the early universe. Results from this analysis are employed in Section 5 where we discuss how the identification of (cores of) clocks becomes progressively more problematic as we go to smaller t-values in the FLRW metric. A summary and some concluding remarks are offered in a final section.

2. The meaning of time

The concepts of time and space are so fundamentally interwoven in our daily and scientific language that it is difficult to extract an unambiguous meaning (or definition) of these concepts. In the present manuscript we shall restrict our investigation to an examination of the time concept in the realm of modern cosmology in which our ordinary language (and its refinements in modern physics theory) is pressed to the utmost. In this section we try to establish a few general points on the meaning of time, which are relevant to cosmology.[3]

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[1] Prior to $\sim 10^{-2}$ s 'after' the big bang (the beginning of primordial nucleosynthesis) there is no clear-cut *observational* handle on physics in the cosmological context, see e.g. Kolb & Turner (1990, p. 74). The gap between this point and the Planck time spans 41 orders of magnitude. (After the COBE and WMAP experiments, however, it is widely believed that inflationary models may have observational signatures in the cosmic microwave background (CMB) radiation.)

[2] The present manuscript focuses on the classical space–time description of the universe and the possibility to identify physical processes which can function as (cores of) clocks. Although time is a classical parameter also in quantum physics, aspects of the problem about time which are directly related to the quantum nature of the physical constituents of the universe will be examined in a separate investigation, see Rugh & Zinkernagel (2008).

[3] In this manuscript we are exclusively concerned with the meaning of time in physics and what may be called ordinary practical language, e.g. we do not address psychological, poetic or religious uses of the concept. The body of literature dealing with the concept of time in general is rather large. J. T. Fraser has estimated that the number of potentially relevant references (books and articles from 1900 to 1980) for a systematic study of time is around 65,000. (cf. Fraser and Soulsby, "The literature of time", pp. 142–144 in Whitrow, 2003).