THE INFLUENCE OF STRONG INTERACTIONS ON THE EARLY STAGES OF THE UNIVERSE

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Abstract. It is shown that the singularity of space-time in Einstein-Friedmann's cosmology can be avoided, if one takes into account the strong interaction of the elementary particles in the earliest stage of the Universe. Under the additional assumption that there exists a maximum temperature of particles and radiation \(T_{\text{max}} \approx 1.9 \times 10^{12} \text{ K}\) in consequence of which the number of hadrons (nucleons) in the early Universe has been greater than today by a factor of about \(10^7\), the Friedmann equation is integrated numerically where the integration constant is fitted by the present values of the mass-density, the Hubble-constant and the temperature of the background radiation. The minimum radius of curvature of the Universe becomes \(1.4 \times 10^{11} \text{ km}\); the density in its neighbourhood remains within reasonable limits of the magnitude of the nuclear density. The early evolution of the Universe with time will be discussed in detail.

Concerning the idea of an universal upper limit for the temperature we follow the considerations of Hagedorn, but in contrast to the existing investigations we take explicitly into account the negative potential energy of the strong interaction according to Yukawa's theory.

1. Introduction and Assumptions

It is well known that the application of Einstein's field equations of gravitation to the cosmological problem, as Friedmann (1922) has shown first, results under the assumption of incoherent matter in a singularity, where the radius of curvature \(R(t)\) of the Universe takes the value zero for a certain initial time \(t = t_0\). This fact has been unsatisfactory for several reasons. A removal of this situation seems to be even more difficult, because Hawking and Ellis (1968), Penrose (1965), and Geroch (1966) have been able to show that under very general conditions the occurrence of singularities is an unavoidable consequence of Einstein's theory, especially independent from the symmetry (homogeneity and isotropy) of the model and from the special form of the energy-tensor, provided that a certain energy condition is fulfilled. But just here the possibility occurs that the initial singularity does not appear in the evolution of the Universe, if in its earliest stages negative pressures, similar to the internal pressure of real gases, play an important role because of the interaction of the elementary particles. That such pressures can exist in consequence of the strong hadron interaction at densities of the magnitude of the nuclear density has been already shown by Libby and Thomas (1969).
In the following considerations we assume as in most previous investigations of the cosmological problem an **homogeneous** and **isotropic** world model with Robertson-Walker metric, so that Einstein's field equations with vanishing cosmological constant \((\Lambda=0)\) will be reduced to Friedmann's differential equations. As an important new aspect we take into account the **strong interaction** of hadrons according to Yukawa's theory, which will result in negative pressures at densities of the magnitude of the nuclear density. In contrast to the fact that the gravitational influence of positive pressures aggravates the singularity, it follows that at sufficiently large negative pressures the Hawking-Penrose energy condition will not be satisfied, so that instead of the singularity of \(R(t)\) a **minimum** radius of curvature \(R_0\) of the Universe results. In this connexion however we have to restrict ourselves to one hadron type only, namely to the exceptionally stable **nucleons**, which means a strong simplification of the problem of matter in the early stage of the Universe, because at the high temperatures and densities in the initial state many other elementary particles have been generated and annihilated.

As a **second** important new aspect the assumption of an **upper limit for the temperature** of about \(1.9 \times 10^{12} \text{ K}\) is added, after reaching of which the temperature of the substratum does not increase by further supply of energy but instead of this the generation of **new** elementary particles, especially of hadrons, happens. Herewith we follow the consideration of Hagedorn (1968), which originates from the experiences in the high energy physics. An indication of the existence of a maximum temperature follows however also from the present value of the temperature of the black body background radiation (\('3 \text{ K radiation}')\), as we will show in the following section. Thus the theory of the \(3 \text{ K radiation}\) just as the consideration of the strong interaction throws a bridge between cosmology and the theory of elementary particles.

A **third** hypothesis is the assumption of **thermodynamic equilibrium** between radiation and matter in the first stages of the Universe. The argument for this is the fact that the background radiation has a spectral energy distribution, which agrees very well with a Planck isotherm of \(2.7 \text{ K}\), as new measurements in the range of radiomillimeter wavelength have shown (Muehlner and Weiß, 1973). Even if the theoretical maximum temperature \((1.86 \times 10^{12} \text{ K} \text{ according to Hagedorn's investigations})\) should not exactly have been reached in the early stage of the Universe, one has to expect that the initial temperature of the Universe has amounted to about \(10^{12} \text{ K}\) (see Section 8).

The following investigation cannot claim, of course, that it solves the problem of matter in the early stages of the Universe completely, although many details can be discussed qualitatively and also quantitatively. We have restricted ourselves to a rather schematic picture of the Universe, which leaves many features of the evolution unconsidered. Especially our considerations need a completion in view of the elementary particle physics and of the nucleosynthesis (helium production). The **neutrino radiation** in the Universe (probably of the order of magnitude of the electromagnetic radiation) will be neglected. Furthermore we restrict ourselves to a **closed finite** Universe of positive mean curvature and spherical (not elliptical) structure. Accordingly