The Very Early Universe

(K. Sato)

In recent years, the research on the very early universe has shown quite remarkable developments. As is well known, this development was brought about by the introduction of the Grand Unified Theories (GUTs) into cosmology. These theories have not only enabled us to trace the evolution of the Universe back to the very early stage at temperatures of 10^{16} GeV or higher, but also introduced various new aspects into cosmology, such as baryogenesis, phase transitions and topological defects (monopoles, etc.). In particular, inflation, which grew out of the study of GUT phase transition, is the most important and fascinating outcome.

INFLATION

At the start, the inflationary universe model attracted people as a model which explains some global features of the present Universe, such as homogeneity and isotropy. Now inflation becomes a much more fascinating idea which may explain everything: the origin of matter as well as the origin of detailed structures, such as galaxies and their distribution. The inflationary universe model has now almost become the standard model for the early stage of the Universe[1].

Along with such developments, however, some problems were pointed out. One of them is that it turned out that we must move the inflationary epoch back to the Planck time and make the interaction of the inflation driving field extremely weak in order to account for the observed inhomogeneity of the Universe. Hence we are obliged to cut off the inflation model from GUT. This drastic revision of the model has given rise to a kind of chaos in the field, since it implies for us to lose the fundamental ground we stand on. At the same time it forces us to study the birth of the Universe itself[2], which is possible only in the framework of quantum gravity. Cosmology of the very early Universe is now waiting for the next big development in particle physics. Superstring theories which try to unify gravity and other non-gravitational gauge interactions may be the one. At the present stage, however, we can say nothing definite.

The second problem is the inflation in an anisotropic and inhomogenous universe. The important consequence of an inflationary universe model is that it explains the reason why our present Universe is so homogeneous and isotropic (the horizon problem). Paradoxically, inflation has been usually analyzed in the context of the homogeneous and isotropic Robertson-Walker model. If the inflation solves the horizon problem under general conditions, we can expect that all the inhomogeneous and anisotropic universes with cosmological constants (the vacuum energy density) evolve towards the de Sitter universe. This conjecture is called "cosmological no hair theorem". Concerning the anisotropic and homogeneous universe, Wald had shown that all the Bianchi types except IX evolve towards the de Sitter solution, and generalization and more detailed investigations have been done by many people (see ref. 3 and papers cited therein). For an inhomogeneous universe, Jensen and Stein-Schabes[4] showed that any inhomogeneous universe will tend towards the de Sitter universe if i) the dominant energy condition and ii) the strong energy condition are satisfied, and iii) the scalar spatial curvature is never positive. Unfortunately, generality of their justification is almost lost by the third condition, because usual inhomogeneities always contain positive curvature regions.

In spite of many efforts to justify the no hair theorem, however, there exists a simple counter example against the no hair theorem, i.e. the existence of the Schwarzschild-de Sitter solution[5]. This is a black hole or a wormhole solution in the de Sitter universe. It is obvious that the no hair theorem does not hold in the strict meaning, because the universe cannot evolve to a homogeneous de Sitter universe in the classical level, if holes exist from the start or once holes have formed.

Recently, Linde[6] considered the evolution of the density fluctuations in the chaotic inflation model and discussed that the high density domains evolve to causally disconnected universes and proposed an eternally existing self-reproducing universe, which is essentially an extension of the multi-production of the universe in the original inflation model (K. Sato et al., see paper cited in ref. 5). It must be, however, mentioned that the "weak no hair theorem" may hold despite the fact that the large amplitude and large scale fluctuations evolve to disconnected universes, because exact solutions which evolve to homogeneous de Sitter universes were found[7] and it was shown that the class of the solutions does not measure zero. This shows the importance of a careful investigation in order to clarify the conditions for the no hair theorem.

BARYOGENESIS

As is well recognized, the interaction of the scalar field which drive inflation must be extremely weak in order to account for the observed large scale structure. This weakly interacting nature leads in general to such low reheating temperatures that the conventional baryogenesis scenario based on GUT becomes difficult[8]. As a possible solution to this problem, recently a new non-GUT mechanism of baryogenesis has been proposed which utilizes the baryon non-conserving process by the anomaly of the electro-weak interactions[9]. Such theories are interesting in that they are pointing out a possible importance of the physics of the GeV to TeV region in cosmology.

QUARK-HADRON PHASE TRANSITION

Recent numerical simulations of lattice QCD strongly indicate the first-order nature of the quark-hadron phase transition[10]. If this is the case, it leads to interesting cosmological consequences. In particular so-called strange quark nuggets will be produced at the cosmological quark-hadron phase transition. As pointed out by Witten[11], such nuggets have planetary mass and could be candidates for dark matter, if they are stable at zero temperature. The interesting point is that it is naturally explained why the ratio $\Omega_{\mathrm{Dark\ Matter}}/\Omega_{\mathrm{Baryon}}$ is o(1), neither $o(10^{-20})$ nor $o(10^{20})$, if dark matter is the quark nuggets[12]. Unfortunately, its zero temperature stability is not established. Furthermore, there are some strong arguments suggesting that they will evaporate thermally at or just after the formation even if they are stable at zero temperature[13]. However, since the production of these nuggets may affect strongly the primordial nucleosynthesis[14] (hence the estimate of the present photon-baryon ratio is changed), study of the quark-hadron phase transition is cosmologically very important.

WEAKLY INTERACTING MASSIVE PARTICLES (WIMPs) AND COSMIC STRINGS

Though not so drastic, some important interplay with particle physics has been observed on the rather recent stage of the Univese. From astrophysical considerations it is shown that dark matter may consist of weakly interacting particles (WIMPs), which are the remnants of the early fire ball stage. Particle theory at present provides lots of candidates for WIMPs[15]. An interesting point is that these candidates are strongly constrained from cosmology and astrophysics. In fact, though not decisive, the only remaining candidates are axions and SUSY ions. They are both intimately connected with the concepts which have played important roles in the recent development of particle pyhysics: gauge anomaly and supersymmetry.

Recent developments in cosmic string theory, in particular, the theory of galaxy formation in terms of cosmic strings[16] should not be overlooked. It seems that except for this type of galaxy formation theory, there is no clear theory at present which gives a consistent scenario of galaxy formation. In this sense, it deserves further study, though there exists as yet no natural model which provokes inflation and at the same time produces cosmic strings of cosmological significance.

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Primordial Nucleosynthesis

(J. Audouze)

Primordial nucleosynthesis which is responsible for the formation of the lightest elements (D, ^{3}He, ^{4}HE and ^{7}Li) might be as important as the overall expansion of the Universe and the cosmic background radiation to prove the occurrence of a dense and hot phase for the Unvierse about 15 billion years ago. As recalled in many reviews (e.g. refs. 1, 2) the standard Big Bang nucleosynthesis leads to two important conclusions regarding (i) a limitation of the baryonic density such that the corresponding cosmological parameter $\Omega_B \leq 0.1$; (ii) a limitation of the number of neutrino flavours to 3-4 consistent with the results concerning the widths of the Z_o and $W^\pm$ particles[3].

The most recent progresses concerning this important problem deal with (i) some recent abundance determinations of the light elements; (ii) the discussion of the validity of the standard Big Bang model; (iii) the chemical evolution of the D and ^{3}He abundances; (iv) the elaboration of models taking into account either the decay of non baryonic particles or the inhomogeneities resulting from the quark-hadron phase transition.

RECENT ABUNDANCE DETERMINATIONS OF THE LIGHTEST ELEMENTS

An excellent review of the D abundances can be found in ref. 4. There is a tentative determination[5] of the D/H ratio in ($z \sim 3$) absorption line QSOs. Concerning ^{3}He a recent reconsideration of the interstellar ^{3}He$^+$/H ratio from radio lines has reduced somewhat but not eliminated the large abundance range reported in previous analyses[6,7].