Chapter I

General Review and Summary

——Astrophysical cosmology——

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§1. Introduction

The present issue of *the Progress of Theoretical Physics, Supplement* is devoted to reviews of astrophysical cosmology on the basis of discussions at six symposia and small group meetings held mainly at the Research Institute for Fundamental Physics since 1967. The group concerned with this research program was originally organized in 1955 and has been engaged in a series of research programs on the stellar evolution, the origin of elements, the structure and evolution of galaxies, the origin of cosmic rays and related problems.[1] Physicists and astronomers involved have changed from one subject to the other, but some have stayed in almost all subjects throughout the whole series. The present article introduces the papers which discuss various cosmological problems on the basis of evolutionary cosmology and the latest knowledge of astrophysics. Taking this occasion, we also introduce a brief history of cosmology studies in Japan and another field of cosmology discussed in some of the symposia. Works belonging to the latter are more or less speculative and no paper dealing with such problems is included in this issue except in §5 of this chapter and §2 of chapter II.

§2. Relativity and cosmology in Japan before World War II

As in other parts of the world, cosmology in Japan was rather mathematical and was almost a synonym for general relativity. Even prior to the general relativity of Einstein, Jun Ishihara developed a theory of gravitation, incorporating electromagnetism and relativity.[2] He translated most papers of Einstein into Japanese and published them in order to popularize the thought of Einstein. Since then relativity has been popular among non-specialists and relativity is still one of the best sold fields of science in the book market in Japan.

Next, Yusuke Hagiwara[3] thoroughly investigated the Kepler motion in the Schwarzschild field and clarified properties of the singularity therein. In addition to his famous works in celestial mechanics, Hagiwara introduced general relativity and cosmology to astronomers and physicists who would otherwise have hardly understood these most difficult subjects.

Yositaka Mimura was most ambitious among others, attempting to incorporate general relativity with quantum mechanics. He called this new theoretical scheme *wave geometry*, by which he claimed that all phenomena from the atomic structure to the universe were explicable. He organized an active group at Hiroshima University to investigate the wave geometry.[4] Although some mathematicians in this group were killed and Mimura himself had been seriously injured by the atomic bomb, he further extended his theory thereafter and established the Institute of Theoretical Physics at Takehara. The Institute remains to be one of the strongest schools in general relativity; Nariai, one of the authors in this issue, was brought up under the influence of Mimura. In spite of his great ambition and effort, wave geometry has hardly been appreciated because of its poor relevance to experiment and observation. However, wave geometry will have to be reevaluated under the light of later development in physics and astronomy.

In addition to the research works of three outstanding theoretical physicists, it should be mentioned that two excellent monographs were published in Japanese, *The Universe* by Takehiko Matsukuma[5] and *Structure of the Universe* by Masaki Kaburaki, both dealing with relativistic cosmology under the light of observations of galaxies.

§3. Cosmology developed in relation to nuclear physics

Immediately after the famous theory of the element synthesis in the early stage of the expanding universe by Alpher, Bethe and Gamow in 1948,[7] Hayashi investigated nuclear processes in a still earlier stage.[8),*] In contrast to the hypothesis in the $\alpha\beta\gamma$ theory that primordial matter consists exclusively of neutrons, an appreciable fraction of neutrons should be converted into protons in equilibrium with electron-positron pairs.

These works opened a new trend of cosmology, different from earlier ones which were mainly concerned with mathematical developments of general relativity. Then Gamow and his collaborators elaborated the hot universe model in various respects.[9] As is well known, this theory failed to explain the jump over nuclei with $A=5$ and 8 by the successive captures of neutrons.

*) This paper is reprinted in p. 248 of this issue.

Another approach to the origin of elements was advocated by Taketani, Hatanaka and Obi,[10] on the assumption that elements are synthesized by thermonuclear reactions in the course of stellar evolution. Their theory was not only motivated by the difficulty in the $\alpha\beta\gamma$ type theory but also based on the attitude that astronomical phenomena should be accounted for, using as far as possible knowledge of physics obtained in laboratories as well as of observational facts, both of which were being accumulated rapidly around 1955. Since heavy elemets are synthesized by thermonuclear reactions in the interior of stars and the relative abundance of heavy elements on Population II stars is far smaller than that on Population I stars, they thought it unnecessary to attribute the synthesis of heavy elements to a process operating before the formation of stars. Then they incorporated the origin of elements with the stellar evolution in such a way that Population II stars were first formed and matter processed in these stars is ejected into interstellar space and condensed to form Population I stars. They further related the above scheme to the evolution of the Galaxy in such a way that the Galaxy was spherical when it was formed and was then flattened.

The ejection of matter was thought to be associated mainly with supernova explosions. Comparing the stellar abundances of elements with the composition of cosmic rays, Hayakawa[11] proposed the supernova origin of cosmic rays, according to which the composition of cosmic rays should represent the abundances of elements formed in the last stage of stellar evolution. The observed results indeed showed an overabundance of heavier elements in cosmic rays.

In order to develop the general scheme proposed by Taketani, Hatanaka and Obi, individual parts in the whole evolutionary sequence were investigated in more detail. One of them was quantitative studies of the 3α-reaction, which takes place in red giant stars and makes possible the formation of carbon and heavier elements from helium, thus overcoming the difficulty of the jump over nuclei with $A=5$ and $A=8$. Theoretical investigations of element syntheses in stars have been studied along these lines by a number of groups.[12] Using the result of 3α-reactions Hayashi and Nishida[13] reexamined the synthesis of light elements in the expanding universe. According to their result, the formation of heavy elements up to oxygen could be explained in this term, if the density of matter relative to that of radiation were much higher than the one accepted today.

We asked around 1956 whether the abundances of elements as well as their dependence on the population of stars are understandable starting from hydrogen alone or they require those primordial elements heavier than hydrogen which may be synthesized at an early epoch of the universe. It was thus recognized as important to investigate the whole of evolution of the universe in a more systematic way. This led us to organizing symposia on the structure and the evolution of galaxies, since these problems had to be understood as a link connecting the stars to the universe.

Apart from the studies related to the element syntheses Nariai[14] discussed turbulent motions in cosmic scale, extending earlier works by Weizsäcker and Gamow.

§4. Studies of metagalactic phenomena

The work of our group had been restricted mainly to theoretical matters before 1959, but the theoretical studies stimulated experimental works which were concerned with galactic and metagalactic phenomena. Cosmic-ray physicists who had been interested mainly in high energy interactions started to work in the chemical composition of cosmic rays in the semi-relativistic region with nuclear emulsion and at very high energies through extensive air showers. The energy spectrum and possible anisotropy of very high energy cosmic rays were also studied through extensive air showers by means of arrays installed at Tokyo and Mt. Chacaltaya. A study of the long-term variation of the cosmic-ray intensity through radio carbon dating and the search of high energy γ-rays were attempted. In connection with the availability of sounding rockets and balloons, feasibilities of observing cosmic X-rays, ultraviolet radiation, infrared radiation and electrons were studied in the 1960's.[15]

In collaboration with these experimental programs, a number of theoretical studies were carried out in order to contribute to the design of the experiments on one hand and to extend our understanding to metagalactic objects. Among them semi-quantitative estimates of the intensity of metagalactic cosmic rays and of γ-rays produced thereby were directly related to cosmology. A series of observations of the diffuse component of X-rays have been conducted since 1965 in intimate connection with cosmology.

Meanwhile several important discoveries came out and their fundametal importance in cosmology was recognized. The quasistellar objects (QSO) were discovered as sizeless radio sources and were identified with optical objects of the largest redshifts. The microwave background radiation was found to represent the black-body radiation of 3°K and was interpreted to be relic of the hot universe, as had been predicted by Gamow. Cosmic X-rays were observed to be far stronger than theoretically estimated and their diffuse component was also found stronger than one had predicted. These discoveries were regarded as emphasizing the importance of evolutionary effects which had not been discussed too seriously.

Facing a new phase of cosmology, we organized a collaboration group, in order to investigate physical processes taking place in the metagalaxy in the framework of evolutionary cosmology. No discussions are made in this issue about models of the universe other than the Friedmann model, but we concentrate ourselves to nuclear, hydrodynamical and thermal processes in an isotropic and homogeneous metagalactic medium expanding monotonically. Particular attention is paid to the study of the formation of galaxies, although further investigation is needed for obtaining a conclusive answer.

§5. New attempts in cosmology

Before going into discussions on astrophysical cosmology we introduce several new attempts which are more or less of speculative nature. These problems are discussed only in this chapter, except for §2 of Chapter II, since they do not belong to the main objectives of this issue.

Although all papers in this issue are based on current physical laws and conventional models of the universe, we have been paying attention to the question whether the basic assumptions are valid or not. There are several attempts at incorporating cosmology with microscopic physics and at introducing unconventional assumptions, as will be briefly described in what follows.

(i) *Global structure of the universe*

It is currently accepted that the global structure of the universe is homogeneous and isotropic, and on this basis the Friedmann model is popular. The postulate implies that the universe is the maximal entity of the physical world and its structure should be as simple as possible. This may be an over-simplification and the universe which we are observing may be an object belonging to one stage of the hierarchy which consists of stars, galaxies and clusters of galaxies. On this point of view an attempt is made to explain the expanding universe as the consequence of an explosion of a massive object heavier than $10^{22} M_{\odot}$.[16]

(ii) *Theory of gravitation*

Various attempts have been put forward for quantizing the gravitational field. Most of them are concerned with field theoretical formulation, but only a few with effects of quantization on the structure and evolution of the universe.

(iii) *Mach principle*

A fantastic problem in cosmology is to investigate the effects of microscopic physical laws on the structure and evolution of the universe. Mach was first to raise a question on the apriori nature of the absolute inertial system postulated by Newton, discussing the rotating bucket experiment. From this stemed the Mach principle according to which metaphysical concepts were discarded and physical phenomena were understood as materialistically as possible, in contrast to the so-called Machism which implies phenomenological philosophy.

In the modern version along this line of thought interactions among elementary particles would be correlated with the structure of the universe. Taketani postulated that all elementary particles interact with each other through the universal weak interaction and attributed its origin including parity violation to the space-time structure.[17] Hayakawa demonstrated how the neutrino emission gives rise to the mirror asymmetry of the universe. He further attempted to correlate fundamental physical constants and the quantum law with fluctuations of the baryon number, the charge number and the lepton number within the Hubble radius.[18] This idea was extended by Hokkyo to explain the mass spectrum of elementary particles on the basis of the radiationless condition in a very early stage of the expanding universe.[19]

Tati attempted to introduce a special inertial system in his theory of the finite degrees of freedom of space time, although consequences of this theory are hardly related to astronomical observations.[20]

It should also be questioned in connection with the Mach principle whether or not the fundamental laws of physics and the universal constants are universal over space and time of cosmic scale, as was raised by Dirac and extensively discussed by Dicke.

Concerning fundamental problems characteristic of cosmology, such as the infiniteness of space and time, we here refer to the debates of ancient eras. Lucretius, against Aristotel, advocated the infiniteness of the universe by a poem of a spear thrown at the edge of the universe. Giordano Bruno in his article titled *On the Infinite Universe and Worlds* discussed the infiniteness and suggested that not only is the earth a member of the solar system but also the solar system is a member of the universe.[21] He seems to have been the first person who thought of galaxies of which the universe consists. Physics in general is reluctant to have infinity, but cosmology cannot help assuming infinity, although the concepts of infinity in these two fields of science seem to be somewhat different.

§6. Summary of the results

The results of our studies of astrophysical cosmology in the last several years are reviewed in individual articles. They are interrelated to each other in the following way.

Physical processes in the metagalaxy are considered to be dictated by the expansion of the universe and the energy supply from galaxies which may have been formed in an early stage of the expansion. The formation of galaxies is one of the most important events taking place in the expanding universe and is discussed in Chapters II, III and IV. The galaxies thus formed may be different from galaxies today and would evolve into those observed today.

The evolution effects may reveal themselves in various phenomena including the background component of X-rays, as discussed in Chapter V. Properties of the intergalactic medium, in particular the magnetic field, are investigated through the Faraday rotation of distant radio sources, the latter being discussed in Chapter VI. Magnetic properties of the Galaxy are also discussed. Before considering the evolutional effect in active radio galaxies we should clarify the intrinsic nature of these objects, as was discussed in Chapter VII. A summary of the results obtained by our group will be described according to the time sequence of evolution of the universe.

A) Sato calculated the formation of light elements in an early stage of the universe on the basis of the hot universe model.[22] The abundances of elements synthesized are far smaller than the cosmic abundances, except D, ^{4}He and ^{7}Li.

B) Matsuda, Sato and Takeda investigated recombination processes in the cosmic plasma in the case of heating by primordial turbulence and gave the degrees of ionization of H.[23]

Hirasawa, Aizu and Taketani and Matsuda, Sato and Takeda dealt with the formation of hydrogen molecules by a catalytic process caused by electrons left after the recombination. Their abundance was found to be as small as 10^{-6} in a uniform medium, whereas hydrogen molecules formed in contracting clouds are sufficiently abundant as a cooling agency.[24]

C) Nariai, Tomita, Kihara, Kondo and Sakai studied the growth of density fluctuations in the expanding universe. They reformulated the linear theory by Lifshitz into a hydrodynamical formalism and, moreover, taking a non-linear approximation into account, investigated the coupling among the acoustic, vortical and gravitational wave modes in the linear theory. Kihara, Kondo and Tomita obtained a critical value of the density contrast for the collapse of a cloud in the expanding universe.[25] The growth of gravitational instabilities is found to be so slow that some other mechanisms should be responsible for the initial density contrast which would result in the formation of galaxies.

D) Sofue and Kondo demonstrated that the formation of clouds as massive as galaxies could take place by thermal instabilities, provided that there were effective heating.[26] Kato, Nariai and Tomita gave a detailed formulation for dealing with thermal instabilities in the expanding universe.[27]

E) Sato attempted to attribute the initial density contrast to primordial turbulence. Studying the temporal behaviour of the size spectrum of turbulence which is excited by inhomogeneous motions before the recombination of hydrogen and then decays by dissipative processes due to viscosity and thermal conductivity, he showed that an inhomogeneity of a size whose mass is comparable to the mass of a galaxy becomes most dominant at the epoch of recombination. Combining this result with the hydrodynamical instability proposed by

Ozernoi and Chernin, Sato, Matsuda and Takeda tried to explain the mass spectrum of galaxies.[28]

F) Tomita, Nariai, Sato, Matsuda and Takeda considered the rate of heating caused by the dissipative decay of turbulence induced by primordial inhomogeneous motions of finite amplitudes in the expanding medium.[29] They calculated the temperature increase associated therewith. As a result, they found that the heating by the primordial turbulence is not so effective as to achieve a temperature high enough for the thermal instabilities.[23]

G) Sato proposed the concept of the observable horizon, beyond which the cosmic matter is opaque. Since the universe is cleared up for thermal radiation at the time of recombination, the universe at this stage can be seen through the observation of the background radiation of 3°K. It is thus suggested that the evolution of proto-galaxies may be revealed by fluctuations of the background radiation with angular sizes as small as 1 minute to 10 second of arc.[30]

H) Hayakawa has conducted an experimental group of cosmic X-rays and has made a series of rocket and balloon observations of diffuse X-rays in the energy range between 100 eV and 1 MeV. Although the results are still to be confirmed, the spectrum of the metagalactic component can be expressed by a power law between 0.2 KeV and several tens of KeV with possible structures in between. It is also likely that the spectrum is steepened above several tens of KeV. As the origin of the metagalactic X-rays, the inverse Compton collisions of energetic electrons accelerated in active galaxies with microwave and infrared photons and the innerbremsstrahlung emitted by the collisions of non-relativistic protons with intergalactic protons are discussed. Particles responsible for the generation of X-rays take part in the heating of the metagalactic medium.[31]

I) Fujimoto, Kawabata and Sofue made a statistical analysis of polarized extragalactic radio sources and suggested a strong indication of the existence of a large-scale metagalactic magnetic field, whose lines of force are uniform at least up to a distance of $z=2$ and run from $l=290°$, $b=-15°$ to $l=110°$, $b=15°$ in new galactic coordinates. The field strength is 2×10^{-9} gauss if we assume $N_e=10^{-5}\text{cm}^{-3}$ as the density of intergalactic thermal electrons.[32]

Magnetic field topologies in galaxies are also discussed. Helical magnetic fields in the spiral arm are interpreted in terms of rolling motions of interstellar gas. Possible magnetic field topologies in the barred galaxy are investigated from a magneto-hydrodynamical point of view and compared with observed distributions of polarization planes of starlight from the Large Magellanic Cloud.[33]

J) Under the light of recent observations on quasistellar objects Aizu, Tabara and Taketani further developed their theory of QSO; QSO represents a particularly active stage of a galaxy in the nucleus of which successive explosions occur. A very small radio structure is explained as due to the synchrotron radiation from an expanding cloud produced by an explosion, and a relatively large structure is explained as a superposition of radio emission from a large number of expanding clouds.[34]

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