Cosmology as ‘Condensed Matter’ Physics *

B. L. Hu †

Department of Physics, University of Maryland, College Park, MD 20742, USA

(UMDPP#89-013, July, 1988)

Abstract

We note that in general there exist two basic aspects in any branch of physics, including cosmology - one dealing with the attributes of basic constituents and forces of nature, the other dealing with how structures arise from them and how they evolve. Current research in quantum and superstring cosmology is directed mainly towards the first aspect, even though a viable theory of the underlying interactions is lacking. We call the attention to the development of the second aspect, i.e., on the organization and processing of the basic constituents of matter (in classical cosmology) and spacetime (in quantum cosmology). Many newly developed concepts and techniques in condensed matter physics stemming from the investigation of disordered, dynamical and complex systems can guide us in asking the right questions and formulating new solutions to existing and developing cosmological issues, thereby broadening our view of the universe both in its formative and present state.

*Invited talk given at the Third Asia-Pacific Physics Conference, June 1988, Hong Kong. Published in the Proceedings edited by Y. W. Chan, A. F. Keung, C. N. Yang and K. Young (World Scientific Publishing Co, Singapore, 1988) Vol. 1, pp.301-314
†Work supported in part by the National Science Foundation under Grant No. PHY87-17155.
In this general talk I would like to share with you some recent thoughts of mine on the direction of cosmological research. They are based on my observation of the evolution of cosmological theories in the past two decades\(^1\) and my partaking of the research of quantum processes in the early universe\(^2\). Development of theories of the early universe\(^3\) in the seventies and eighties is partly an extension of relativistic cosmology developed in the sixties based on classical general relativity theory. Its most notable examples are the so-called "standard model" constructed from the Friedmann-Robertson-Walker universes and the "chaotic cosmology" based on the Bianchi universes. Indeed one major component, the Kaluza-Klein cosmology, is a class of higher-dimensional anisotropic universe. There is also infusion of new ideas from particle physics and quantum field theory - most notably the inflationary cosmology, the semi-classical cosmologies, and quantum cosmology. These new cosmological theories rely in various degrees on the working of many gravitational, quantum and statistical processes in the early universe. These physical processes have close analogies in condensed matter physics. Examples are phase transition in inflationary cosmology, particle production and backreaction in semiclassical cosmology, quantum tunneling in quantum cosmology, etc.\(^2-4\). It is against this backdrop that I shall attempt to make some synthesis of ideas and introduce some new ones. I should point out that none of the specific points discussed here is new, but by rendering them in some particular ways I hope that new insight will emerge which may prove useful in guiding future research in cosmology.

By studying the attributes of these models and the nature of these physical processes, I come to realize that there are two basic aspects in the formulation of any cosmological model. One aspect involves the basic constituents and forces, the other involves the structure and dynamics, i.e., the organization and processing of these constituents as mediated by the basic forces or their derivatives. The first aspect is provided by the basic theories describing spacetime and matter. The second aspect in addressing the universe and its constituents is cosmology proper.

## 1 Two Basic Aspects in Physics

It is not difficult to recognize that actually these two aspects permeate throughout almost all subfields in physics, or science in general. Examples of the first aspect in physics dealing with the "basic" constituents and forces are general relativity, quantum mechanics, quantum electrodynamics, quantum chromodynamics, grand unified theories, supersymmetry, supergravity, quantum gravity and superstring theories. The second aspect dealing with the structure and dynamics is the subject matter of biology, chemistry, molecular physics, atomic physics, nuclear physics and particle physics. The former aspect is treated today primarily in the disciplines of elementary particle physics and general relativity. The latter aspect is treated today in the discipline known collectively as condensed matter physics. In this sense we can, for example, regard nuclear physics as condensed matter physics of quarks and gluons, the collective manifestation of QCD force.

Note, however, the duality and the interplay of these two aspects in any discipline. On the one hand the basic laws of nature are often discovered or induced from close examina-
tion of the structure and properties of particular systems - witness the role played by atomic spectroscopy and scattering in the discovery of quantum mechanics and atomic theory, accelerator experiments in advancing particle physics. On the other hand once the nature of the fundamental forces and constituents are known one attempts to depict reality by deducing possible structures and dynamics from these basic laws. Thus the study of electrons and atoms via electromagnetic interaction has been the underlying theme of condensed matter physics. Deducing nuclear force from quarks and gluons via QCD remains the central task of nuclear research today. From general relativity one attempts to deduce the properties of neutron stars, black holes and the universe, which is the theme of relativistic astrophysics and cosmology.

Note that many known physical forces are not fundamental (in the sense that they are irreducible), but are effective in nature. Molecular forces and nuclear forces are such examples. One may also regard gravity as an effective force. Note also that many disciplines contain dual aspects. This is especially true in the developing areas, in which the basic forces and constituents of the system are not fully understood. For example particle physics deals both with the structure and the interactions. This is seen in the dialectic relation of, say, quantum flavor and color dynamics and the duality of compositeness and elementarity. Similar aspects exist in superstring and quantum gravity theories.

2 Two Basic Aspects in Cosmology

What about cosmology? The above-mentioned dual aspects are certainly apparent. What is new is that in addition to matter (as described by particles and fields) we have to add in the consideration of spacetime (as described by geometry and topology). In the first aspect concerning constituents and forces, there are also two contrasting views\(^5\): The "idealist" takes the view that spacetime is the basic entity, the laws of the universe is governed by the dynamics of geometry. Matter is viewed as perturbations of spacetime, particle as geometrodynamical excitons\(^6\). These ideas, as extension of Einstein's theory, are not that strange as they may appear. For example it is well-known in gravitational perturbation theory that high frequency perturbations off a background spacetime behave like relativistic fluid. Closer to this idea are the Kaluza-Klein and superstring theories. There, particles are representations of internal symmetries, graviton the resonant modes of strings. Although a geometric theory is difficult to construct, the philosophical overtone of these theories is clear. By contrast the "materialist" takes the view that spacetime is the manifestation of collective, large scale interaction of matter fields. Thus according to Sakharov\(^7\), gravity should be treated as an effective theory, like elasticity to atomic forces. This is expressed in the induced gravity program\(^8\). Despite its many technical difficulties, this view still evokes some sombering thoughts. It suggests among others that the attempt to deduce a quantum theory of gravity by quantizing the metric may prove to be as meaningful as deducing QED from quantizing elasticity. In recent years the apparent contrast between particle-fields and geometry-topology has dissolved somewhat in the wake of superstring theory\(^9\). The fact that the same concept can be viewed in both ways may indeed offer some new insights into
the nature of our universe.

As for the second aspect in cosmology, i.e., the manifestation of basic forces in astrophysical and cosmological processes, one sees that almost with any subdiscipline of physics there is a corresponding branch of astrophysics. Hydrodynamic and radiative processes in classical astronomy and astrophysics are based on Newtonian gravity and Maxwellian electromagnetism. The application of nuclear physics to astrophysical phenomena in the 50’s and 60’s has successfully explained nucleosynthesis and neutron star structure. The 70’s and 80’s saw the advent of particle astrophysics and inflationary cosmology based on the grand unified theories, and semiclassical cosmologies based on curved-space quantum field theory\textsuperscript{1).} However, the central theme of cosmology which addresses the state of the universe as a whole is more than the sum-total of its individual components, as depicted by the many subdisciplines of astrophysics. There are broader issues special to the overall problem of how the universe comes into being and why it should be the way it is, which touch on the basic problems of quantum mechanics and relativity theory. The inquiry of these issues will necessarily force us back to the first aspect of cosmological research discussed above.

3 Two Directions of Cosmological Research

Depending on the relative emphasis one puts on these two aspects, current research on cosmological theories follow roughly two directions:

A) Cosmology as consequences of quantum gravity and superstring theories.

B) Cosmology describing the structure and dynamics of the universe

In the first direction, quantum cosmology as represented historically by the work of Wheeler, DeWitt, Misner, Hawking, Hartle, Gell-Mann, Coleman and others\textsuperscript{10}) deals more with the boundary conditions and constraints of quantum gravity as it applies to our universe than with the theory itself. Many of the questions raised in current research such as the wave function, the density matrix, the vacuum state, the nature of time, conditional probability, etc., touch on the fundamental problems (especially their problematic intersections) of general relativity and quantum mechanics, as manifested in a rather special and unique system which is our universe\textsuperscript{11}). Oftentimes we have to extend our consideration of physics to superspaces\textsuperscript{12}) and other universes\textsuperscript{13}). In this context the universe is regarded as a special medium where the conflicts of quantum mechanics and relativity are acted out. It is not exactly the study of the consequences of a quantum gravity theory in the same sense as particle astrophysics or inflationary cosmology with respect to GUT theories. And it is with this emphasis that its importance should be properly attached. Likewise, many current studies of so-called ”superstring cosmology” based on the picture of spacetime as a smooth manifold is, in my opinion, at best irrelevant and likely totally wrong. They are incorrect not just because they attempt to draw implications without an established theory, but more so because they do not address the correct problems. One exciting aspect of superstring theory is that not only does it depict a new picture of spacetime based on extended geometric objects but it provides one with the methodology to quantify new concepts such as topology change, etc.\textsuperscript{14}). To say something new, i.e., different from conventional cosmology based on
manifold spacetime superstring cosmology should at least begin with a different concept of spacetime. Doing it otherwise misses the whole point.

In this first direction one could also include inquiries or proposals made which view the universe as manifestor of physical laws, as formulator of rules, as processor of information, etc.\textsuperscript{15}. This direction of cosmological research touches on the basic laws of quantum mechanics, general relativity and statistical mechanics. In this field the formulation of meaningful problems are almost as important as seeking their solutions. Progress will be slow but the intellectual reward is profound.

4 Cosmology as ‘Condensed Matter’ Physics

By now I hope the meaning of this figurative description is clear. Please bear in mind that by "condensed state" I refer both to matter and spacetime. Cosmology is the study of the organization and processing of matter as well as spacetime points. To be explicit I have sketched in Table I some major ingredients of condensed matter physics, nuclear physics and the physics of the early universe. The early universe is included here because it invokes many physical processes which directly affect the overall structure and dynamics of spacetime (e.g. particle production and backreaction, quantum vacuum energy and inflation, etc.). Table II outlines the major themes of recent development of condensed matter physics. Notice the increasing importance attached to nonlinear, nonlocal and stochastic behavior of complex systems. The neighboring column lists problems of a similar nature in the cosmology of the early universe. In contrast to Table I, the problems listed here are mainly representative in nature and are largely undeveloped. Such a comparison is aimed at stimulating new thoughts along these lines. None of these ideas are due exclusively to me, nor are they completely new - many of them have been toyed with some twenty years ago\textsuperscript{5,6}. The difference between now and then is that 1) concepts and techniques in particle physics, especially superstring theory, have developed to the degree that the mathematical formulation of these problems has become possible, and 2) advances in condensed matter physics such as phase transition and critical dynamics, order-disorder behavior, dynamical systems, complex systems, etc. have opened up new possibilities in probing the organization and dynamics of matter in various states. These techniques and ideas may provide useful hints in understanding how spacetime takes shape, how the universe evolves, what determines its content and how its many different structural forms develop.

For illustrative purpose I have listed in Table III some sample problems of this nature in cosmology, with respect to the universe in its present, early and primeval states. I have only mentioned the essential underlying ideas, with some sample references, should the reader be interested in the details.

By organizing these problems according to some general theme and by providing some overall perspective, novel as it may be, I hope this could generate some interest in pursuing cosmological research in a new light - as "condensed matter" physics of general relativity and quantum gravity.
5 New Elements

In examining these new problems and concepts we see that according to this view two major ingredients will likely contribute to shaping a new direction of cosmological research: One is topology and the other is stochasticity, both for matter-field and spacetime-geometry systems. For the concepts of spacetime-geometry what is more important is not geometry, but topology; not topology, but point sets. For basic laws, one’s focus moves from the rules to construct content to the rules to construct rules. As for structure, what is more important is not regularity, but randomness: not order, but chaos - or, more interestingly, order out of chaos; not simplicity, but complexity - or complexity out of simplicity. In summary, the new direction seems to be forged with topological ideas applied to spacetime and fields and statistical ideas applied to structures and basic laws. Cosmological research would benefit from recognizing and harnessing these new developments.
| CONDENSED MATTER PHYSICS | NUCLEI AND PARTICLES | EARLY UNIVERSE |
|-------------------------|---------------------|----------------|
| - electromagnetic interaction | - strong interaction | - quantum fields in curved space |
| **CONSTITUENTS** |
| - electrons | - quarks, gluons | - particle-fields |
| - atoms | - mesons, baryons | - spacetime-geometry |
| **FORCES** |
| - electronic-ionic | - chromo-electromagnetism | - general relativity + GUT |
| - chemical-molecular bonds | - nucleon force | - gravity as effective force |
| **COLLECTIVE EXCITATIONS** |
| - lattice and electron | - particle spectrum | - Casimir effect and particle creation from magnification of quantum fluctuations |
| - phonon | - bound states | - graviton and particles as excitation of spacetime |
| - plasmon | - resonances | |
| - exciton | - solitons, skyrmions | |
| **PHASE TRANSITIONS** |
| - solid-liquid-gas | - quark-hadron phase transition | - of Higgs field at $t_{GUT}$: inflationary transition |
| - superconductivity | | - of spacetime at $t_{Planck}$: black hole-string transition |
| - metal-insulator, etc. | | |
# TABLE II - DEVELOPMENT OF "CONDENSED MATTER" PHYSICS

| CONDENSED MATTER PHYSICS | COSMOLOGY |
|--------------------------|-----------|
| as the organization and processing of | NONLINEARITY, NONLOCALITY, STOCHASTICITY |
| atoms and electrons | spacetime and matter |

**FRAMEWORK OF SYSTEMS:**

1. Ordered Systems

- lattice + electrons + excitations
- spacetime (as smooth manifolds) + perturbations
- fields + fluctuations

2. Disordered System

- topological defects: strings, domain walls, etc
- topological structures of gauge fields
- multiply-connected spacetimes

3. Random System

- amorphous state, spin-glass, random network
- random fields in curved spacetime
- stochastic spacetimes

4. Dynamical System

- chaos-order
- metric and topological entropy
- fractals
- organization and processing of matter (e.g. galaxy distribution)
- spacetime (e.g. chaos in mixmaster)

5. Complex System

- spin glass, neural network, parallel processor
- information theory
- self-reproducing universes
- spacetime as organization of points (e.g. Borel sets)\(^\text{15}\)
- physical laws as processing of propositions (e.g. quantum logic)\(^\text{15}\)
# TABLE III - SOME SAMPLE PROBLEMS

| PROBLEMS | THEMES | SAMPLE REFERENCES |
|----------|--------|-------------------|
| **A. Present Universe** | | |
| 1. galaxy correlation function | fractal dimension | 16 |
| 2. voids and foam-like structure | topology of matter distribution | 17 |
| 3. galaxy formation | cosmic strings, topology of field configurations | 18 |

| **B. Early Universe** | | |
|-----------------------|--------|-------------------|
| 1. chaos in Bianchi cosmology | chaotic dynamics - topological entropy | 19 |
| 2. strange attractor in Kaluza-Klein and superstring cosmology | dynamical systems | 20 |
| 3. ”self-reproducing” universes | cellula automata | 21,22 |
| 4. hierarchical universes | complex systems | 23,24 |

| **C. Primordial Universe** | | |
|----------------------------|--------|-------------------|
| 1. Regge calculus, lattice universe | - simplicial complex | 25 |
| 2. spacetime foam | - topological classes, probability distribution | 14 |
| 3. stochastic fields and spacetimes | - stochastic calculus | 26 |
| 4. ”Birth” of the universe | as interface dynamics | 27,28 |
| 5. causal structure | from ultrametricity | 29,30 |
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