RANDOMNESS AND REGULARITY IN COSMIC STRUCTURE

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SUMMARY

A newly developed theory of cosmic evolution based on Einstein's theory of gravitation and on a symmetry postulate called the strong cosmological principle shows that the gross structure of the universe is characterized by a collection of simple numerical regularities reminiscent of those that govern atomic structure.

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In his Nobel Lecture, 'Events, Laws of Nature, and Invariance Principles,' Wigner pointed out that physics does not seek to explain nature completely. Events are determined partly by natural laws (simple underlying regularities) and partly by initial conditions, which have 'a strong element of randomness.' Since the time of Galileo physicists have sought and found increasingly general and simple natural laws; but about initial conditions 'we know virtually nothing. . .. We have ceased to expect from physics an explanation of all events, even of the gross structure of the universe, and we aim only at the discovery of laws of nature, that is, the regularities of the events.'[1]

In the following paragraphs I shall outline a theory, based on existing physical laws -- in particular, Einstein's theory of gravitation -- and on a generalization of an accepted symmetry principle, that seeks to explain both the gross structure of the universe and the aspect of events that Wigner asserted lies outside the scope of physics. The theory confirms and amplifies Wigner's insight that initial conditions have a strong element of randomness. Yet it shows that their <u>statistical</u> properties are predictable. In this respect the present theory of cosmic structure and evolution resembles the quantum theory of atomic structure, though the origin of the underlying indeterminacy is different in the two cases. Moreover, the masses, gravitational binding energies, and epochs of formation of self-gravitating systems (or, more precisely, the expectation values of these quantities) are found to have discrete spectra of possible values. Like the energy levels of an atom, these can be predicted from first principles and expressed in terms of fundamental physical constants.[2]

The basic premise of the theory, which I call the strong cosmological principle, asserts that the universe admits a statistical description that in no way serves to define a preferred position or direction in space; and this description is complete. The new, and at first sight paradoxical, element of this postulate is the assertion of completeness. For we know that statistical descriptions of ordinary macroscopic systems are inevitably incomplete. They always lack some kind of non-statistical information. For example, if we specify the temperature and pressure of a liter of hydrogen in a state of thermodynamic equilibrium, we completely determine all statistical properties of the gas; yet the positions and velocities of the individual molecules (or, in a quantal description, the quantum state of the many-particle system) remain undetermined. But what significance can we attach to the positions of individual molecules in a statistically uniform distribution that is both infinite and unbounded? By definition, there is no preferred frame of reference in which they can be measured. This example suggests, and a more complete argument confirms, that non-statistical information is simply not present in a cosmic distribution satisfying the strong cosmological principle. It is excluded by the symmetry of the distribution, a symmetry that cannot be realized on any smaller scale. This is the ultimate source, I believe, of the 'strong random element' that Wigner discerned in the initial conditions of macroscopic physics and that plays such a crucial part in irreversible macroscopic processes.[3]

Einstein's theory of gravitation implies that a universe satisfying the strong cosmological principle expands uniformly from a singular state of infinite density. Detailed physical arguments indicate that the conditions prevailing near the beginning of the cosmic expansion were much simpler than they are now. Matter was in a state of local thermodynamic equilibrium, and local density fluctuations, if present at all, were exceedingly small. These considerations suggest the second of our two postulates: <u>the initial state was one of global thermodynamic equilibrium at zero temperature</u>. This is clearly the simplest assumption one can make about the initial state of the universe. If its consequences have not previously been worked out, it is perhaps because people felt that it was <u>too</u> simple -- that the complexity of the present-day universe requires a corresponding degree of complexity to be present in some form in the initial state.[4]

Our two postulates completely specify the initial state of the universe. Its subsequent development presents a series of well-defined physical problems, from an analysis of which there emerges the following picture of cosmic evolution.

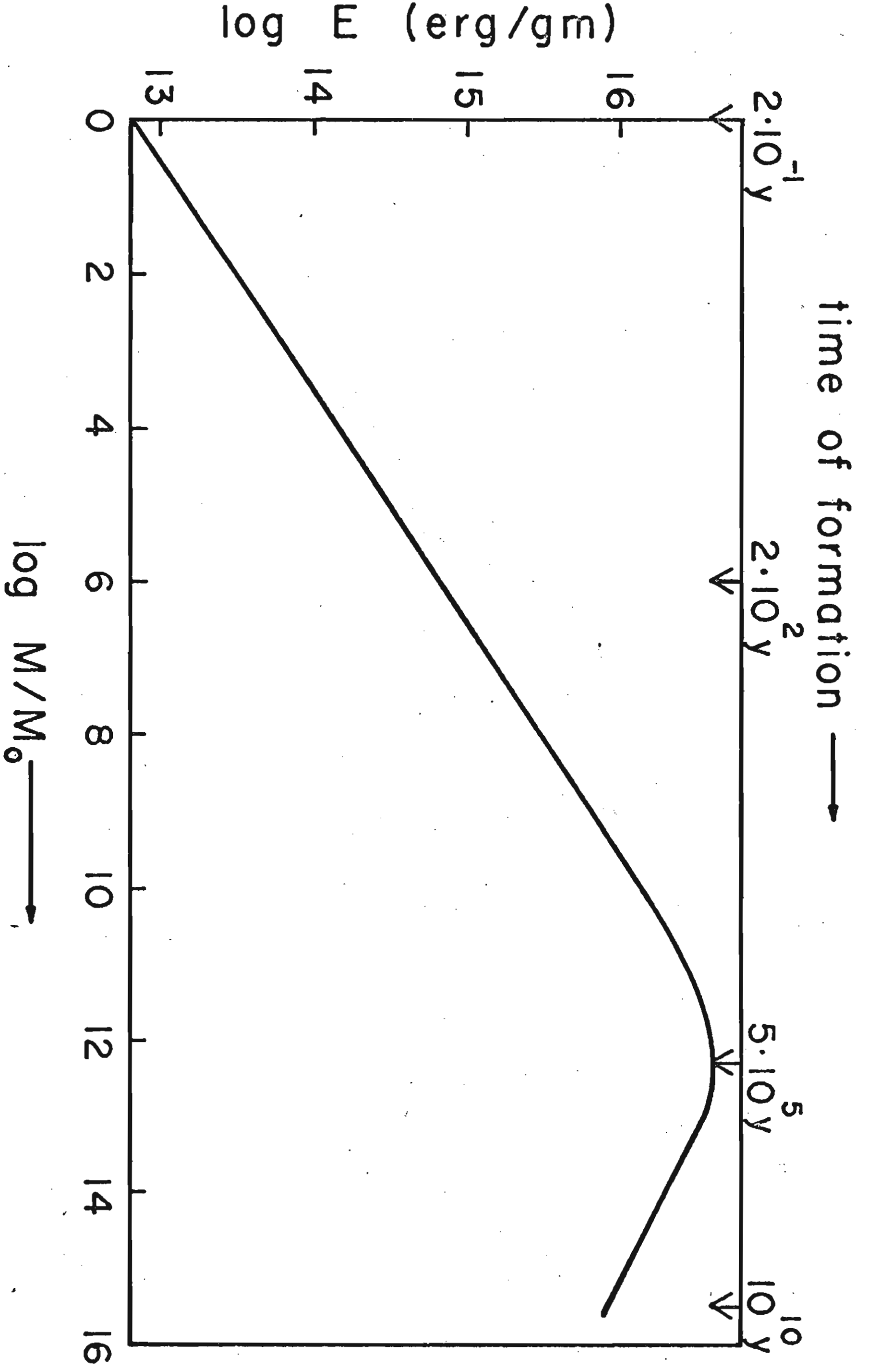
Phase 1: equilibrium phase ($t = 0$ to $t \simeq 1.3 \times 10^3$ sec). Thermodynamic equilibrium prevails (except as regards nuclear reactions); significant density fluctuations are absent; the internal energy of the gas decreases and, just before the end of this phase, becomes negative. This phase ends when, as a result of Coulomb interactions, the isothermal compressibility becomes infinite and the gas becomes thermodynamically unstable.

Phase 2: transition phase ($t \simeq 1.3 \times 10^3$ sec to $t \simeq 2.6 \times 10^3$ sec). Large-scale density fluctuations form, analogous to those responsible for the phenomenon of opalescence in a vapor near its critical point. The density fluctuations give rise to local gravitational fields which in turn accelerate the gas. At the end of this phase the internal energy and pressure are dominated by gravitational and macro-kinetic contributions.

Phase 3: gravitoturbulent phase ($t \simeq 2.6 \times 10^3$ sec to $t \simeq 6 \times 10^6$ sec). There now prevails a hitherto undescribed type of strong turbulence which I call gravitoturbulence, because it is dominated by local gravitational fields. A theoretical analysis shows that most of the energy in the gravitoturbulent spectrum at a given time t resides in density fluctuations whose dimensions lie between $L_1 = a\,t$ and $L_2 = c\,t$, where a denotes the speed of sound and c the speed of light. The form of the gravitoturbulent spectrum is determined by generalized thermodynamic considerations. During this phase the gravitational energy per unit mass -- which will later serve to bind self-gravitating systems -- continually increases in magnitude, as does the relative amplitude of the density fluctuations, or density contrast. The gravitoturbulent phase ends when the density contrast has increased to a value somewhat greater than unity, and the first generation of self-gravitating systems is about to separate out.

Phase 4: clustering phase ($t \simeq 6 \times 10^6$ sec to the present). The distribution of gravitational energy among structures of different mass is now more or less frozen in, but the density contrast continues to increase. The first self-gravitating systems separate out at the beginning of this phase. Later a second generation of self-gravitating systems separates out. The second-generation systems are clusters of first-generation systems. Still later a third generation, whose members are clusters of second-generation systems, separates out, and so on. In this way a nested sequence of self-gravitating systems comes into being: the raw material from which subsequent evolutionary processes have fashioned the astronomical hierarchy.

(See Figure.)


log E (erg/gm)
13
14
15
16
0
2
4
6
8
10
12
14
16
log M/M$_o$ ⟶
time of formation ⟶
2·10^{-1} y
2·10^2 y
5·10^5 y
10^{10} y

The accompanying Figure summarizes the theory's quantitative predictions. It shows the initial gravitational binding energy per unit mass as a function of mass and indicates the epochs of formation of key self-gravitating systems. Evolutionary considerations allow us to identify the first-generation systems with protostars, the most tightly bound systems with the most massive galaxies, and systems intermediate between these two extremes (on a logarithmic scale) with globular star clusters. The theory also predicts the masses and binding energies of the largest galaxy clusters, namely, those being formed at the present time. Bearing in mind that the observations cover a mass range of fifteen decades and that the theory contains no adjustable parameters, the agreement between theory and experiment leaves little to be desired.

Equally as striking as these numerical successes are the formulae that give the masses, initial binding energies, and epochs of formation of self-gravitating systems in terms of fundamental physical constants. These are illustrated by the following two examples, the first of which gives the number of protostars in a protogalaxy of maximum binding energy, the second the number of protons in such a protogalaxy:

$$M^{\dagger}/M^{*} = 10(m_p/m_e)^{3/2}(\hbar c/e^2)^{3/2}$$

$$M^{\dagger}/m_p = 60\ (m_p/m_e)^{3/16}(\hbar c/e^2)^{63/16}(e^2/Gm_em_p)^{3/2}.$$

The pure numbers that appear here have the following meanings: m_p/m_e = ratio of proton to electron mass; $\hbar c/e^2$ = fine-structure constant; e^2/Gm_em_p = ratio of electrostatic to gravitational force between an electron and a proton. Thus the simple regularities that characterize the structure of atoms are echoed on the cosmic scale, and in that echo there is more than a hint of Pythagoras's music of the spheres.

NOTES

1. E. P. Wigner, 'Events, Laws of Nature, and Invariance Principles,' Nobel Lecture, 1963 (Stockholm, 1964).

2. A detailed mathematical account of the theory referred to here was presented at the Brandeis Summer Institute of Theoretical Physics, July, 1968, and will be published in 1969 under the title 'Cosmogonic Processes' by Benjamin & Co.

3. The connection between the strong cosmological principle and the arrow of time is developed in two articles: 'The Strong Cosmological Principle, Indeterminacy, and the Arrow of Time' in 'The Nature of Time' (ed. T. Gold), Cornell; and 'Cosmology and the Arrow of Time' in 'Vistas of Astronomy' (ed. A. Beer), to be published.

4. It has also been argued that the cosmic microwave background discovered by Penzias & Wilson in 1965 could only be interpreted as radiation left over from an infinitely hot initial state. As I have shown elsewhere, however, the observed radiation can more naturally be attributed to ordinary astronomical processes in an initially cold universe ('Black-body Radiation in a Cold Universe', Astrophysical Letters, 1, 99, 1968); 'Gravitational Collapse, Cosmic Black-body Radiation, and the Origin of Astronomical Systems', Gravity Research Foundation first prize, 1968.

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