COMMITTEE I
Unity of Science: Organization and Change in Complex Systems

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COMMENTS

by

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on

Jacob D. Bekenstein's

GRAVITATION AND THE ORIGIN OF LARGE STRUCTURES IN THE UNIVERSE

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Comments by Nicholas Kurti

on

Gravitation and the Origin of Large Structures in the Universe.

by Jacob D. Bekenstein.

It was after some hesitation and with considerable apprehension that I accepted the invitation to discuss Professor Bekenstein's paper. I asked myself how can a physicist whose main interests are in low temperature physics and magnetism make useful comments on a paper by a widely acknowledged expert on cosmology? However I found encouragement in the fact that these conferences are devoted to the, as yet unanswered, question of the Unity of Sciences and I concluded that not being able to conduct an interdisciplinary or non-specialized dialogue would be tantamount to negating the very purpose of these gatherings.

My misgivings evaporated as soon as I started reading Professor Bekenstein's paper. Here is, at last, a concise, critical yet readily understandable account of the development of mankind's - or rather of astronomers', physicists', chemists' - ideas about the origins and the evolution of the Universe. It reads rather like a good detective story: when the case looks like being solved new clues, new circumstances, come to light which seem to render the earlier conclusions untenable - and the process is repeated page after page, decade after decade.

We begin with the Newton-Jeans hypothesis that gravitation leads to condensation of matter - chaos followed by some sort of an organization - provided that some "seeds" existed which could grow into large inhomogeneities, e.g. stars. But would this process still take place in an expanding universe? Yes, it will, showed Jeans, albeit more slowly.

So far so good. But we know, or believe, that in its early ages the Universe consisted mainly of radiation, and condensation could not set in until the dynamics of the Universe became dominated by matter, i.e. when it was about one thousandth of its present size. The statistical probability of early seeds growing into conglomerations of the order of magnitude of stars is so small that one had to postulate that in the early, radiation-dominated Universe there have been seeds much larger than statistically predicted.

If the stars could be regarded as the basic units of the Universe this would be the end of the story. However, by the mid-1920s it became clear that galaxies are the basic units of the Universe and Professor Be kenstein tellingly compares the relation star-galaxy to the relation cell-organism. If one dared to go a step further one might say that just as galaxies, clusters of galaxies and superclusters form the Universe, so do human individuals, their groupings etc. form human society - or, to be less homocentric - so do different living organisms of different structures or degrees of
117 organization make up Life on Earth.

From here on the picture becomes less clear, and there seem to be several unsolved questions. Thus, did stars come first and organize themselves into higher structures - galaxies, clusters etc.? Or did the organization of the Universe start with superclusters which then broke up into smaller units? These two scenarios and an "explosion" scenario are discussed and the pros and cons are argued in detail but it seems that, unlike in detective stories, it is no good turning to the last page to discover the solution. In fact this splendid paper could have as its motto the last 10 words: "the concept (of a local gravitational entropy quantified by the Weyl tensor, suggested by Penrose) has yet to be put
124 to the crucial test".

I hope I shall be forgiven this attempt to survey briefly the points made by Professor Bekenstein, but I wanted to convey the pleasure and the thrill I experienced when reading his paper. Let me now make some comments and ask some questions - at the risk of parading my ignorance. Although some of them do not directly refer to the text they are closely related to the ideas exposed.

Let me begin with the beginning, i.e. the "Big Bang". I find the idea of a "beginning", of a time "zero" conceptually difficult to accept. For me time is "timeless" and stretches to infinity both in the past and in the future. I wonder
145 which of the two following interpretations - both of which would get me out of

my difficulties - is the correct one. 1) The time of the big bang, calculated by extrapolation into the past, is not the <u>origin</u> of time, but indicates the moment when something happened, and that the Universe in its state of infinite density and temperature and of zero radius (see page 19) existed from time immemorial before the big bang. Or, to put it into Old Testament language: $-\infty$ (Genesis I.1. In the beginning God created the heaven and the earth) - t (negative) Gen.I.2. And the earth was without form and void and darkness was upon the face of the deep. And the Spirit of God moved upon the face of the waters) - 0 (The Big Bang, Gen.I.3 And God said, Let there be light: and there was light) - t (positive) ⟶

2) An alternative interpretation of the origin of time comes naturally to a low temperature physicist. In discussions about the chronology of the period of time following immediately upon the Big Bang one finds statements that such a thing happened at 10^{-40}s or 10^{-10}s or 10^{-6}s after the big bang. Do these very short time intervals bear any relation to similar time intervals we deal with today? Do these ever-decreasing times <u>converge</u> to a time <u>zero</u>, or is the origin of time an asymptotic, unattainable limit of the time scale just as sbsolute zero is an unattainable singularity of the temperature scale?

The following true story illustrates my point. After a lecture to schoolmasters about low temperature physics in which I mentioned that temperatures of the order of a millidegree kelvin (0.001°K) can be determined to an accuracy of about 0.0001°K. I was asked by a member of the audience how accurately the triple point of water (273.16K, an important thermometric fixed point) was known. I gave a few 10^{-3}(0.001)K as the limit, an answer which prompted the riposte "How can you then measure 0.001°K to an accuracy of 0.0001K ?" An excellent remark which was never put to me in that form and I must admit to my shame that it took me about ten seconds to gather my wits and give the questioner an answer which satisfied him.

Another point which I hope will be discussed is the state of the Universe immediately before the Big Bang (p. 19 and pp.23-24). Was the temperature infinitely high or very low? I do not think that to try to choose between these alternatives is meaningful. Although we talk about "absolute" temperatures there is nothing absolute about them. True, one can talk about something being hotter or colder than something else - one can quantify this by running a heat engine between the two "things", but it is often more useful to consider the entropies of the systems. Let us compare one g-atom of liquid ^{3}He and the electron gas, i.e. the conduction electrons in one g-atom of metallic copper. At say 1°K the entropy of the 6 x 10^{23} ^{3}He atom is many orders of magnitude larger than the entropy of the 6 x 10^{23} electrons. In fact the electron-gas has virtually zero entropy - the "cold, smooth, low-entropy state" of page 24. Not until one gets to about 1000°K does the entropy of the electron-gas become perceptible and leaves its ordered quantized state. On the other hand at 1°K, or even at 10^{-3}K, the mean kinetic energy of the electron corresponds to a temperature of many thousands kelvin.

One final point which, I assume, will come up frequently during the deliberations of this committee, is the use of the entropy concept in many different disciplines. I believe that physicists, chemists and engineers agree on the whole about the meaning of entropy, both in the thermodynamical and in the statistical-mechanical sense. But are we sure that entropy plays a similar role, is conceptually the same, when used in cosmology, or biology or information theory or economics? I hope that we shall formulate definitions for the various areas and uantify the entropy changes in various processes. Would it be too far-fetched to ask how much does the entropy change when a healthy, normal human being suddenly dies as a result of an accident?

28 October 1985.