The State of Understanding of the Nature and Evolution of the Observable Universe

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I offer in the first section an outline of major steps to the present standard and accepted theory of the large-scale nature and evolution of our universe. I comment on some open issues in Section 2.

1. Steps to our present understanding

The exploration of our physical world may be classified in a hierarchy of size scales. Some scientists examine the organization of molecules of atoms in biological systems, in all the complexities of their interactions. Others examine the atoms, a simpler task because there is a limited number of different atoms with appreciable lifetimes. And low atomic number atoms are simple enough to allow precision tests of the quantum theory of their structures. Others examine the behavior of the nuclei of atoms, and others the substructures of the protons and neutrons in atomic nuclei. On larger scales there is the rich study of the complexity of what is happening on our planet Earth. The wonderful varieties of physical situations on other planets and moons in our Solar System allow quite different things to be studied. At this meeting Lisa Kaltenegger discussed research by her and colleagues that has taught us about the planets around other stars in our neighborhood, in all their variety.

The stars are organized in galaxies, another subject of active research. Galaxies appear in concentrations ranging from groups of a few galaxies to clusters of hundreds of large galaxies. Groups and clusters tend to be concentrated in superclusters. But there is something new on still larger scales: observations reveal no higher layers of structure. We are instead presented with a universe that looks much the same everywhere and in all directions: a clumpy sea of galaxies and groups and clusters of galaxies (a statistician might say the universe is well approximated as a stationary random process: fluctuations of the mass distribution around a fixed mean value have the same statistical character everywhere and in all directions). This is why we can attempt to find a testable theory of the universe, rather than a theory of a level in a hierarchy of phenomena on larger and smaller scales.

Einstein had argued on philosophical grounds that it ought to be this way, before large-scale homogeneity was observed. In Einstein’s vision inertial motion could be meaningful only relative to how matter in the neighborhood is moving. But his general relativity theory gives meaning to inertia even in an otherwise empty universe, provided it has a spacetime. To avoid what he considered to be philosophically unacceptable Einstein proposed a boundary condition: the universe has no edges, no preferred position. Einstein proved to be right. We still debate whether he was right for the right reason.

I must hasten to add that there certainly may be boundaries to the universe as we know it. This is a common conjecture among those exploring ideas about the state of the universe in the very remote past. The universe can be examined, in varying degrees of detail, by detection of radiation that has been traveling toward us since the early stages of expansion of the universe. We have only indirect hints to what lies beyond that, which certainly makes it difficult to check ideas. But within the region that can be observed is an abundance of phenomena. Typical sizes of superclusters are roughly 1% of the greatest distance we can observe. This is room for some million superclusters of groups and clusters to be studied in varying degrees of detail.

The first good evidence that the observable universe averages out to homogeneity came from the discovery that we are in a sea of hard X-rays, and soon after that that there also is a sea of microwave radiation (wavelengths of millimeters to centimeters, and now known as the Cosmic Microwave Background, or CMB). Both radiation backgrounds are very close to isotropic: coming at us at nearly the same intensity from all directions. This isotropy means either that we are close to the center of an inhomogeneous but spherically symmetric universe, or else that the radiation is close to homogeneous. The former seems quite unlikely. There are enormous numbers of other galaxies that seem to be equally good homes for us. If the universe were not close to homogeneous then our galaxy would be in an exceedingly special place, near the center of symmetry, and an observer in almost any other galaxy would see that the radiation backgrounds vary across the sky. The more reasonable notion is that an observer in any galaxy would see about the same thing, because the universe is filled with near homogeneous seas of X-rays and the CMB. The near homogeneity of the matter distribution is best tested indirectly, by the relativistic theory of how departures from a homogeneous mass distribution would perturb the distribution of the CMB. Measurements of the distributions of matter and the CMB are found to be consistent under the assumption of general relativity theory. This also means that general relativity passes a demanding test.

Georges Henri-Joseph-Edouard Lemaître, a Belgian Catholic Priest and physicist, was the first to recognize observational evidence that the universe is expanding. I believe that in the years around 1930 Lemaître understood Einstein's general relativity theory better than anyone else. He also knew the astronomers' observations that the light from distant galaxies is shifted to the red, to longer wavelengths, as if the light had been Doppler shifted by motions of the galaxies away from us. And he showed that this behaviour is to be expected if the universe is homogeneous and expanding. He recognized that general relativity predicts that a static homogeneous universe is unstable: the slightest disturbance sets it collapsing or expanding. The astronomers' redshifts say it is expanding.

Lemaître's expanding universe theory was based on observations, but not enough to make a serious scientific case for the expanding universe theory. More convincing evidence came from measurements of the intensity spectrum (the distribution of energy with frequency) of the CMB, the sea of microwave radiation. The results are summarized in Figure 1. The thin dotted curve represents the intensity spectrum at thermal equilibrium. The coloured curve near the peak represents measurements, not theory. The symbols represent other measurements at discrete frequencies. The distinctive thermal shape of the measurements is what would be expected if this were a fossil remnant from an early state of expansion of the universe, when it was dense and hot enough to have relaxed to statistical equilibrium, which of course includes thermal radiation. Under standard local physics the expansion cooled the radiation, leaving it with the observed thermal spectrum at the present measured temperature, 2.725 K (measured above absolute zero).

It was natural to ask whether processes in the universe as it is now might have produced this thermal spectrum. But the universe as it is now is seen to be transparent at these wavelengths. No absorption means no relaxation to thermal equilibrium. The conclusion seems quite convincing: this radiation is a fossil left from when our expanding universe was dense and hot.

(In more detail, we may note that as the universe expanded this sea of radiation did not go away – in a homogeneous universe there is no place for it to go. Or perhaps better put: every photon moving away from us is on average matched by a photon moving toward us from afar. The expansion of the universe shifts CMB photons to longer wavelengths, and decreases the photon number density, which together conspire to preserve the thermal spectrum).

I count Figure 1 among the iconic images that succinctly represent great advances in natural science, here evidence that our universe is evolving.

Preservation of the thermal shape of the CMB intensity spectrum is expected under standard local physics if the expanding universe is close to homogeneous. But the preservation does not depend much on the rate of expansion of the universe. This means that the fact that the measured spectrum is close to thermal does not seriously test general relativity. This theory is tested by measurements of distances and redshifts. Saul Perlmutter discusses these measurements in these Proceedings. And relativity theory is tested in quite another way by comparison of the predicted and measured evolution of departures from homogeneous distributions of matter and the CMB. The measurements are far more precise and accurate than ever I imagined when I was working out these ideas in the early 1980s. And the theory fits these precise measurements.

(The situation might be described in a little more detail as follows. The theory predicts that small departures from homogeneity in the early stages of expansion of the universe tend to grow under the influence of gravity. But the hot state of the early universe would have ionized the matter, the free electrons would have scattered the thermal radiation, and that would have made matter and radiation act as a fluid. Fluids support pressure waves. The nature of the waves is controlled by boundary conditions. Thus the boundary conditions in an organ pipe set the fundamental tone, or wavelength. Boundary conditions for pressure waves in the expanding and cooling universe are set in time. When the universe had expanded and cooled to about 3000 K the plasma combined to neutral atoms. That rather abruptly set matter free from the radiation. The pattern of pressure waves at that point was imprinted on the matter and radiation. Gravity caused the matter waves to grow more prominent, eventually becoming galaxies and clusters and superclusters of galaxies. The radiation propagated to us more or less freely, presenting us with the measured slight anisotropy of the CMB).

There is an interesting complication. To make the predicted patterns of matter and the CMB agree with what is observed we must postulate that the ordinary matter of which we are made (so-called baryonic matter, after the baryons in atomic nuclei) is about one sixth of the total mass of the universe. The other five sixths is assumed to be a new form of matter that interacts weakly if at all with ordinary matter and radiation. This hypothetical component, known as dark matter, must behave at least roughly like an ideal monatomic gas with very low initial temperature (the temperature remains low in a stream of this dark matter, but when orbits cross in growing mass concentrations the mix of orbits approximates a hot gas).

The fit of observed and measured distributions of matter and radiation also requires the presence of the cosmological constant, #. Saul Perlmutter describes in these proceedings how he and colleagues detected #, in quite a different way. That is, we have two quite independent lines of evidence pointing to the presence of #. This makes a strong case. And the agreement of theory and measurements of the distributions of matter and the CMB makes a strong case that general relativity gives a useful approximation to what happened.

2. The present situation

Our theory is incomplete. We do not know what the hypothetical dark matter is. We do not know why Einstein's # has a truly curious value in the context of what we now understand about fundamental physics. And we do not have much evidence about what the universe might have been doing before it could have been described by classical general relativity theory and the rest of conventional physics. But all physical theories are incomplete. Thus the theory of electromagnetism that Maxwell wrote down a century and a half ago is still taught, in better notation, because it is very useful. But this theory fails on the scale of atoms. It is now established that Maxwell's equations are a limiting case of quantum electrodynamics. This theory works very well through the scales of molecules and atoms and atomic nuclei and their contents. But what about the infinities of quantum electrodynamics? Perhaps some are the fault of the perturbative methods of computation. Perhaps others will be resolved by making quantum electrodynamics a limiting case of a still deeper theory, maybe superstrings. That calls for a lot more work to be done. The situation is similar in cosmology. Our present theory passes a considerable network of tests based on observational evidence of what happened from the time light elements formed, when the temperature was about *T* # 109 K, to the present, at *T* = 2.725 K. And the tests are dense enough to make a convincing case that the theory is a useful approximation, though incomplete.

The incompleteness of our theory of the large-scale nature of the universe is disappointing: we wish we had done better. But it is exciting: we may be sure the incompleteness is offering us hints to a better theory. It is a good bet that a better theory will contain elements that behave like dark matter, #, and all that, because the present theory fits a considerable variety of evidence of these components. But that is to be seen, of course.

There is the line of thought that our present theory of the large-scale nature of the universe is incomplete at least in part because the suitability of the universe for our existence is to be attributed to Intelligent Design. I rely on the expertise of George Coyne, SJ, and former director of the Vatican Observatory, who I quote, as accurately my memory allows, "Intelligent Design is bad science and bad theology". To observe and attempt to make sense of the material world in which we find ourselves is good science, and I trust acceptable theology.

Scientists whose judgements I respect argue that our present standard theory may be incomplete in part because it does not take account of the Anthropic Principle. This supposes a multiverse, an unlimited variety of universes with different properties, including different and various laws of physics. Or else there is one universe in which well-separated parts are quite different. We must find ourselves in a universe, or a part of the universe, that has properties consistent with our existence. So is our universe thus selected from an ensemble to fit our needs? Or instead are we selected to live with what the universe offers? There are good arguments for the former. But I am uneasy about the freedom to decide when to invoke the Anthropic Principle. In effect, shall we be tempted to give up on some particularly challenging issue and declare that "then something magic happens"?

It certainly is right and appropriate to marvel at how well our environment suits our needs. This is in part a consistency condition. Our species became organized when conditions allowed it: Earth's climate has been relatively stable and benign since the last ice age, allowing agriculture to flourish and support other organized activities. This is an eventuality. Other conditions are fixed by physics. It is a Good Thing for us that ice is less dense than water, for if ice sank as it formed it would be much less likely to melt in the summer, maybe turning planet Earth into a permanent snowball. But in an imaginary alternative universe in which ice sinks while the physical situation otherwise is much like ours I imagine conditions suitable for us could obtain on a planet that has a greater abundance of radioactive elements. Greater internal heating by radioactive decay would be a greater source of heat to melt deep-sea ice. A more demanding Good Thing is that atomic nuclei are bound, though just marginally. A hypothetical universe with slightly weaker nuclear forces would contain only the lightest element, hydrogen. If physical conditions were otherwise similar to ours then gas spheres with the masses of planets and stars and larger would form and cool on Kelvin-Helmholtz time scales, millions of years. Molecular hydrogen would form by catalysis by free electrons, and I suppose molecules would form snowflakes of some kind. The familiar ones are interestingly complex. Might much more complex hierarchies of complex structures of the vapour, liquid, and solid phases of atomic and molecular hydrogen form, in millions of years, in many repetitions of the experiment, in the vast number of gas spheres in the vast number of galaxies in this universe? In short, the Anthropic Principle takes it that “beings” complex enough to change the environment, such as people on bulldozers, or sheets of bacteria, require conditions not vastly different from ours. But I suspect our imaginations are too limited to sort through all situations capable of something deeply complex, in our universe or a multiverse.

I am impressed by the vast number of planets in our observable universe. Lisa Kaltenegger explained the evidence that there are at least as many planets moving around stars as there are stars. In a large galaxy such as ours there are some 1010 stars roughly like the sun. There are roughly 1010 large galaxies in our observable universe, which means at least # 1020 planets. Conditions on or in most of these planets surely are quite inappropriate for us. But if one planet in a million offered a suitable home for beings capable of something deeply complex it would mean our observable universe has on the order of 1014 potential homes. Why such an immense number? Do we ascribe this to the Anthropic Principle? Surely a galaxy or two would do for us.

Despite my unease about the Anthropic Principle I must agree that a universe with |#| large enough to prevent anything much to happen at the rates set by the rest of the physics in that universe would not produce anything interesting. If # truly is a free parameter then we do require something outside our present and envisioned physics, perhaps some version of the Anthropic Principle. But one might imagine that a deeper fundamental physics to be discovered will predict an effective # whose present value and rate of change are consistent with what is observed. I hope the community will not give up pursuing this dream, and all the many other attempts to understand what to make of our physical universe as we find it.