COSMOLOGY FROM ROBERTSON TO TODAY

In a retrospective look at a simpler universe of cosmological ideas, a Soviet cosmologist emphasizes the seminal contributions of the American cosmologist H. P. Robertson.

Yakov B. Zel'dovich

The outstanding contributions of H. P. Robertson to cosmology make giving this memorial lecture a great honor for me—a feeling that is enhanced by reading the list of the eminent previous Robertson lecturers.

To appreciate Robertson's work, one must understand its background. Albert Einstein created the general theory of relativity, which is the modern theory of gravitation. In this theory, both gravitation and cosmology are geometrized. Einstein himself imagined a spatially closed, time-independent universe. Alexander Friedmann found—or guessed—a nonstationary cosmological solution to the Einstein equations. Edwin P. Hubble's discovery of the redshifts of the distant galaxies confirmed the idea that the universe evolves through its expansion.

An American quartet of cosmologists

Such was the situation in the late 1920s when Robertson came to cosmology. His approach was logically and mathematically rigorous. Assuming exact uniformity (equivalence of different places) and exact isotropy (equivalence of all spatial directions), he found all possible "cosmologies." The result coincided with Friedmann's guess but immensely increased its credibility.

Robertson then investigated all the observational properties of the solutions: the dependence of the redshifts, angular dimensions, brightnesses and so on, of astronomical objects as functions of their ages at the time the light we now receive from them was emitted. The work of Robertson and three other outstanding American scientists, Hubble, Richard C. Tolman and Milton L. Humason, deserves special recognition. This quartet did more than any other group to ascertain by observations and theoretical calculations the theory of the uniform isotropically expanding universe.

Yakov B. Zel'dovich (deceased 2 December 1987) was a professor at the Institute for Physical Problems, Moscow, USSR. His interests ranged widely, including hydrodynamics, general relativity and cosmology. A brief biographical note is included in PHYSICS TODAY, May 1987, page 107, on the occasion of the award of a 1985 Dirac Medal to Zel'dovich. He delivered the remarks published here at the H. P. Robertson Memorial Lecture on 29 April 1987 at the National Academy of Sciences, Washington, DC.

Standard hot Big Bang model of the universe

The next steps, which were taken after Robertson had shifted to other activities, are well known. First came the discovery of the cosmic microwave background radiation in 1965 and the development of the hot Big Bang theory. One cannot compete with Steven Weinberg's book *The First Three Minutes* (Basic Books, New York, 1977) for a lucid presentation of this theory. In connection with the hot Big Bang, I wish to stress two points.

The first point is primordial nucleosynthesis. The calculations and observations of the composition—of hydrogen, helium-4, deuterium and helium-3—provide a brilliant confirmation of our ideas about the first few seconds of evolution. On the other hand, we know the overall density of hydrogen and the other elements in stars and gas. Comparing it with mass determinations of the total density of matter based on observed gravitational interactions, we find that 90 percent of the total density is made up of some unknown type of matter—the so-called dark matter. Fundamental physics does not preclude the existence of as yet unknown forms of matter, but it does not provide definite predictions about its properties.

The second point now under active study concerns the large-scale structure of the universe. On scales less than 100 megaparsecs the distribution of density is very inhomogeneous. (For comparison, the observational distance limit, often called the horizon, is on the order of 10 000 megaparsecs.)

Large-scale structure and inflation

Visible matter is concentrated in stars, which form galaxies. The galaxies are also distributed unevenly, in clusters and superclusters of galaxies. There are giant regions, with linear dimensions up to the order of 50–100 megaparsecs, that are practically without galaxies—the so-called voids. The theory of gravitational instability of uniform matter distributions explains this observation qualitatively. But we are far from having an exact and rigorous quantitative explanation of the structure of the universe around us.

The second major achievement of the last decade is the inflationary theory of the very early universe developed primarily by Alan Guth in the US and by Andrei D. Linde and A. A. Starobinsky in the Soviet Union. (See Linde's article in PHYSICS TODAY, September 1987, page 61.) Assuming the universe was once filled with a scalar field corresponding to a negative pressure, the inflationary theory predicts an exponential expansion of the universe. This scenario leads to the conclusion that the universe is now practically flat and that its total density is simply related to the Hubble constant. Moreover, it explains why the conditions are the same in regions that would be too far apart to communicate in the simple Friedmann–Robertson–Walker picture of the universe.

Expansion and the scalar field

In my opinion, the most important result of the scalar field idea is its explanation of the expansion of the universe. Friedmann and Robertson did not explain the expansion now observed; they simply said the universe is now expanding because it was expanding earlier. The negative pressure idea, put into the general relativity equations, leads to gravitational repulsion instead of attraction. It is this repulsion that gives the initial velocity of expansion for the later plasma phase in the evolution of the universe. The scalar field assumed in the inflationary theory has never been observed in the laboratory. Perhaps the field is not a scalar field, but another geometrical term (R^2 or $R^2 \ln R$, where R is the space–time scalar curvature) in the fundamental equation of general relativity. This term is similar in many respects to a scalar field. In any case, gravitational repulsion and the ensuing exponential expansion now seem to be well established, at least qualitatively.

The quantum zero-point oscillations of the scalar-field (or geometry) are the source of the initial perturbations that led to the present inhomogeneous distribution of visible matter. The zero-point oscillations are a direct consequence of the Heisenberg uncertainty principle: The scalar field strength ϕ is similar to the coordinate of a point mass; the time derivative of the field $\dot{\phi}$ is similar to the velocity or momentum. The uncertainty principle means that ϕ and $\dot{\phi}$ cannot be determined together exactly, and this means that they cannot be exactly the same everywhere. The idea that the zero-point oscillations are the seeds of galaxy formation was formulated by Andrei Sakharov in 1965, though in another context and before the inflation theory.

The fluctuations accumulated over large distances are not necessarily small. L. P. Grishchuk and I argued in 1978, before the inflation theory, that the density must be quasiuniform, but that the metric of the universe as a whole can be very different from isotropic and uniform. This leads to a picture opposite, in some respects, to that of Robertson. Robertson assumed isotropy and uniformity of the entire universe *a priori*. The contemporary point of view is that the universe's metric is not at all isotropic and uniform. The observed region of the universe seems to be uniform and isotropic (and, moreover, flat), just because it is a very small part of the whole universe.

To give a simple analogy, the surface of an elephant is not similar to a sphere and even less so to a flat surface. But every small part of the elephant's surface (skin) is nearly flat, just because it is small. The wrinkles on a small piece of the elephant's skin are a model of the initial perturbations that lead to galaxy formation. The rigorous mathematical description of this complex behavior is elegant and close to the spirit of Robertson's investigations. The super-large-scale space-time metric has the form of the so-called quasi-isotropic solution ($ds^2 = a^2 [dt^2 - dr^2]$), introduced by E. M. Lifshitz and Isaac M. Khalatnikov in 1963; actually we need only a special case of it. The Friedmann–Robertson–Walker scale factor a does not change with time, but it does contain as a factor an arbitrary function $f(\mathbf{r})$ with sufficiently small spatial gradients. The detailed form of $f(\mathbf{r})$ is determined by the

H. P. Robertson: A Brief Biography

Howard Percy Robertson was born in Hoquiam, Washington, in 1903 and earned his undergraduate and master's degrees at the University of Washington. He completed his PhD in 1925 at the California Institute of Technology, and he then spent three years in Göttingen and Munich as a National Resarch Council Fellow. He returned to the US in 1928 as one of the best-trained mathematical physicists in the country. An expert in quantum mechanics, he soon became interested in relativistic cosmology and concentrated his efforts on it at Princeton University (1929–47) and at Caltech (1947–61). As Zel'dovich points out, Robertson made many fundamental contributions to this subject and to the development of observational tests for various cosmological models. He was not only an outstanding researcher but also a gifted teacher. As World War II approached, Robertson shifted his efforts to scientific military work, particularly in ordnance and intelligence. After the war he continued to act as an adviser at the highest levels of the Department of Defense until nearly the end of his life. He died in California in 1961 following an automobile accident.

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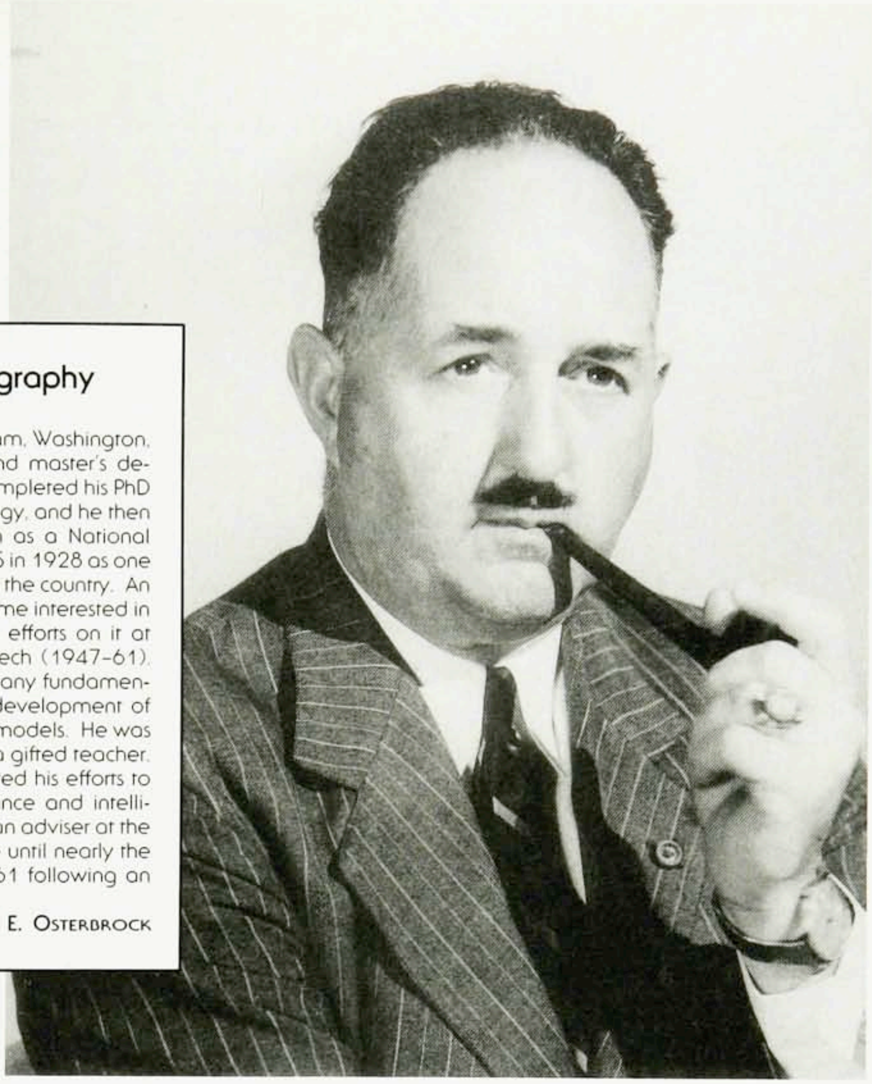

Howard Percy Robertson

particular set of quantum fluctuations in the inflationary stage. It is remarkable how much complexity can be described by this single function!

Looking beyond the cosmological horizon

What is the future of cosmology? The scalar-field theory, which takes account of quantum fluctuations, leads to the possibility of an everlasting universe. The regions where the scalar field is increasing because of fluctuations expand longer and more rapidly than other regions, and this expansion can lead to a fluctuating but everlasting general picture. On the other hand, it is possible that the universe (if it is closed and includes a scalar field) was born in a single quantum jump out of nothing. As Edward P. Tryon in the United States and Pyotr I. Fomin in the Soviet Union pointed out, such a birth is possible first of all because the total energy of the closed world is zero. The energy of the field is compensated for by gravitational interaction with negative potential energy. This general property holds for all closed manifolds in general relativity.

Ideas of spontaneous birth were like *belles dormantes*—sleeping beauties—before the inflationary theory. That theory has built a bridge between the small newborn universe and the large plasma-filled universe, and the even greater universe of today. The previously mentioned problems associated with the early universe and its ties with the structure of the universe today will characterize cosmology in the coming decades.

Cosmological caveats

It should be pointed out that cosmology is now applying highly hypothetical fundamental physics that has not been confirmed by any experiment. We are extrapolating physical laws to energies 10^{15} times larger than those achieved in the most powerful accelerators. A new branch of science is born: the application of astronomical knowledge to find (or at least to constrain) the fundamental laws of physics in regions inaccessible to direct experiment. We are in the position of the paleontologists, with only fossils or remnants to study directly.

"The universe is the poor man's accelerator" is the motto of this new direction of science. It should always be used in conjunction with Lev Landau's skeptical description of astrophysicists: "Often in error, never in doubt."

But my final words return to Robertson. His work was exact and logically irreproachable. All the more or less fantastic later speculations would not be possible without the work of Einstein, Friedmann, Hubble and—of course—Robertson!

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This article was edited by Donald E. Osterbrock, Lick Observatory, University of California at Santa Cruz. ■