Measuring the Universe

# The Beginning of the Universe

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**One of the most astonishing discoveries of the 20th century was Hubble's discovery of the expansion of the Universe**

Prior to this discovery people had shared a view of space and time as unchanging and independent of matter. Such a fixed space with a river of time, both unaffected by physical bodies, had been the stage for Newtonian mechanics. However, Hubble's discovery in the 1920s came at the right time.

In 1916, Einstein had published his *General Theory of Relativity*, and few years later Friedmann had found solutions of Einstein's equations corresponding to an expanding Universe. Cosmic space and time became related to matter; the geometrical properties of space and its temporal evolution became inseparable from the material content of the Universe and its large-scale structure.

## Cosmic expansion

Cosmic expansion is of tremendous importance for studies of the beginning of the Universe and the formation of the bodies and structures we observe. Since cosmic space expands, it follows that everything was closer together many epochs ago. As all cosmic objects have some fixed physical size, it is clear that there must have been some epoch in cosmic history, eons ago, when it was not possible for galaxies to exist as independent, individual structures. At earlier epochs, not even stars could exist; earlier still, even individual atoms

NASA and K. Lanzetta (SUNY)

The very first stars lit up the pitch-dark heavens just a few hundred million years after the tremendous explosion that created the cosmos would not fit into the much smaller spatial volumes; before that, even atomic nuclei would have been too large, and so on.

The concept of the beginning of the Universe as a specific event in the past is deeply rooted in many religions and was discussed by the ancient philosophers. However, Hubble's discovery suggested something profoundly different. In mythology, the beginning of the Universe was a one-time event, resulting in a world "ready to use," similar to what we see today. The expansion of space, however, proves that the Universe must have **evolved**, since it was impossible for organised structures (such as atoms, molecules, planets, stars and galaxies) to exist from the very beginning.

### Going backward in time

Reversing (as a thought experiment) cosmic expansion and extrapolating backward in time, we can estimate the age of the Cosmos from its current expansion rate. The age of the Universe is the time which has passed since space and matter started to expand as a result of the Big Bang - the beginning. The best present-day estimate for the age of the Universe is 13.7 x $10^9$ years. How far back in time we extrapolate is really a matter of taste. As we go closer and closer to the Big Bang, the physical conditions in the Universe were more and more extreme. It is clear that, at some point, the physical theories we know must break down. However, we can safely discuss processes in the primeval cosmic plasma a few seconds after the Big Bang. The conditions there were not that different from what we can study in nuclear reactors today. Even a mere fraction of a second after the beginning, the physical conditions in the Universe (i. e. the density and temperature) are still familiar, as they are similar to what we can produce in particle accelerators.

To know the changing rate of cosmic expansion we need to know the amount and the form of matter in the Cosmos

### How it all began?

The beginning of the Universe is only the ultimate starting point in the history of cosmic "beginnings." A series of early phase transitions created the initial density fluctuations, which later served as the seeds of cosmic structure - superclusters, clusters and galaxies. It was the beginning of structure formation. In inflationary models, the universe starts with a net baryon number very close to zero; at the beginning, there was as much matter as antimatter. An excess of matter can only be generated from this initial situation after inflation under the following conditions: the baryon number is violated; the charge (C) and charge-parity (CP) symmetries are violated; the universe was not in thermal equilibrium for a period during bariogenesis. As the CP symmetry violation is known from laboratory physics, we believe that we understand why the Universe is made of matter rather then a mixture of matter and antimatter. All this happened in a tiny fraction of a second after the Big Bang.


WMAP team

The WMAP spacecraft after a deployment test of its solar arrays

We are made of chemical elements. Our bodies and everything around us is made of baryonic "stuff," organized in molecules which are themselves composed of atoms. The atomic form of matter was created in several processes during cosmic evolution. The lightest isotopes, those of hydrogen, helium and lithium, were created during the first three minutes after the beginning. Later it was too cold and the density was too low for hierarchical build up of more complex atomic nuclei. The process of primordial nucleosynthesis was interrupted and resumed only after the first stars had formed. To explain the observed abundances of the light elements in the Universe, it was postulated that, at the beginning, the Universe must have been hot. Matter and radiation were in thermal equilibrium. The existence of the remnant radiation, which today has cooled to just 2.7 Kelvin, was predicted. The discovery of this relict radiation in the microwave domain in the 1960s was a major turning point in the history of cosmology. The expansion of the Universe, the abundances of the light elements, and the existence and properties of the microwave relict radiation are the fundamental observational facts supporting the Big Bang scenario.

The beginning of our planetary system and our own planet took place when the Universe was approximately three times younger than it is today

The beginning of the formation of heavier chemical elements started in stars just few hundred million years after the Big Bang. This process has been continuing throughout the whole of cosmic history, altering the chemical content of galaxies. Looking deep into space we are looking into the remote past (due to the finite speed of light), thus we can actually observe the process of structure formation and the chemical evolution of galaxies.

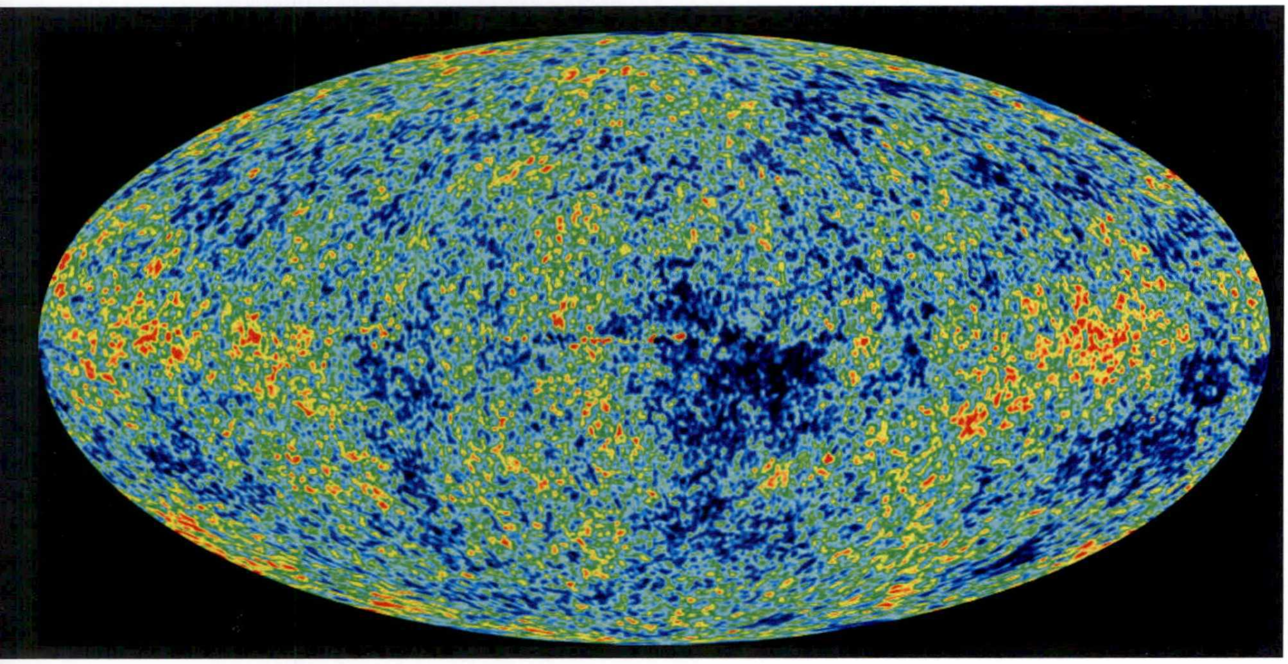
Galaxies and clusters of galaxies formed from the initial density fluctuations as a result of gravitational instability. They came into existence in the Universe soon after the Big Bang, less than $10^9$ years after the beginning. Most stars were formed when the Universe was five times younger then today.

In the last ten years we have discovered planets beyond our Solar System. Today we know of more than one hundred extrasolar planets. We observe protoplanetary disks and we are becoming increasingly convinced that planet formation is a natural part of the process of stellar formation, and that planets should not be uncommon in the Universe. Our planet, as well as the Sun and other planets in the Solar System, was formed from the same protostellar nebula, some 4.5 x $10^9$ years ago.

Life started on the Earth soon after the planet cooled enough for complex molecules to form. The beginning of life is estimated to have occurred about 3.5 x $10^9$ years ago.

### Polish contribution

Scientists from the Copernicus Astronomical Centre in Warsaw have taken an active role in this process of revealing cosmic evolution. The process of stellar evolution has been studied by Professors Bohdan Paczyński (now at Princeton University) and Józef Smak, among others. Recently, Professor Janusz Kałużny measured the age of the one of the oldest known stars in the Universe. Professor Roman Juszkiewicz has contribu-



WMAP team

**The first all-sky picture of the infant universe taken by the WMAP satellite. Encoded in the patterns are the answers to many age-old questions, such as the age and geometry of the Universe**

Galaxies gravitationally lensed by a galaxy cluster

Hubble Space Telescope

ted to the understanding of the fluctuations in the relict microwave background and of galaxy formation and has created original methods for measuring the mean density of matter in the Universe. The author of this article has studied clouds of intergalactic matter and has estimated the intensity of the ionising ultraviolet background radiation, which played an important role in the structure formation epoch. Krzysztof Górski (now at JPL, Pasadena) and Radosław Stompor (now at UC, Berkeley) have made important contributions into the investigation of the relict microwave radiation. Ewa Łokas and Michał Chodorowski have contributed to the theory of the galaxy formation. Aleksander Wolszczan, who discovered the first extrasolar planets, started his career at the Copernicus Centre in the 1980s. Professor Mirosław Giersz studied the structure and stability of the globular clusters - systems hosting the oldest stars. Currently, Professor Michał Różyczka and his group are developing numerical simulations to study in detail the process of planet formation.

Physical cosmology is a relatively young science. It only started after Hubble's discovery of the expansion of the Universe, Einstein's formulation of General Relativity and the discovery of the microwave background. Yet within only a few decades, people were able to measure the size of the Universe, its age and chemical composition, and to put major events in cosmic history into chronological order. This process of discovery still continues. In the last few years, observations of distant supernovae (exploding stars which outshine their host galaxy for a couple of days) at the edge of the observable Universe, and measurements of the temperature fluctuations of the microwave relict radiation, have proved that the Universe is filled with some strange, nonbarionic forms of matter and energy. About one third of the whole material content of the Cosmos is in the form of dark matter - nonbarionic particles forming massive halos around galaxies and clusters of galaxies. About two thirds is in the form of dark energy - even more mysterious than dark matter - causing the acceleration of cosmic expansion.

Many physicists consider dark energy, acting against gravity to accelerate the expansion of space, the biggest unsolved problem in physics. It is being speculated that dark energy is related to the properties of the physical vacuum. Solutions to this problem will most probably require a new, deeper physical theory of the fundamental properties of matter. Quite unexpectedly, studies of the largest accessible scales - the Universe as a whole - have revealed something of extreme importance about the nature of fundamental processes. The presence of dark energy in Cosmos may be the result of processes which took place almost at the very beginning of the Universe. ■

> We still do not understand the properties of the Universe at the very beginning. No existing theory can describe the initial singularity and no theory can explain why the Big Bang had to happen

**Further reading:**

Steven Weinberg W. (1994). *The First Three Minutes: A Modern View of the Origin of the Universe.* New York: Basic Books.

Alan H. Guth, Alan P. Lightman (1998). *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins.* Cambridge MA: Perseus Publishing.