What Energy Drives the Universe?

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What energy drives the universe? Where did this energy come from? Before trying to answer these questions, let us remember that *energy of matter in the universe is not conserved*: $dE = -pdV$. Volume V of an expanding universe grows, so its energy decreases if pressure p is positive.

Consider, for example, the hot universe created in the Big Bang. According to the hot Big Bang theory, the total number of photons in the universe practically does not change since the moment of its creation. However, the average energy per photon, which is given by the temperature of the universe T, decreases as $1/a$, where $a(t)$ is the scale factor ("the size") of the universe. This happens because the energy of each photon is inversely proportional to its wavelength, and the wavelength is stretched by the expansion of the universe. Therefore the total energy of radiation in the universe (the total number of photons multiplied by the energy per photon) decreases as $1/a$ during expansion of the universe.

Standard description of the universe becomes possible when its temperature becomes smaller than the Planck temperature $T_p \sim 10^{32}$ K. Since that time, the temperature decreased to $T_0 = 2.7$ K, and the total energy of radiation decreased by a factor of $T_p/T_0 \sim 10^{32}$. Observations show that the total energy of radiation in the universe now is greater than 10^{53} g. At the Planck time, the energy of each photon was 10^{32} times greater, so the total energy of radiation was greater than $10^{53} \times 10^{32} = 10^{85}$ g. Extending this investigation back to the cosmological singularity, where T was infinite, one finds that in order to create the universe in the Big Bang singularity, one should have *an infinite amount of energy.*

We are coming to a paradoxical conclusion: before the Big Bang there was NOTHING, and then suddenly we got A HUGE AMOUNT OF ENERGY. After that, one can only loose energy, so the origin of energy of matter remains a mystery. This is just one of the many problems of the hot Big Bang theory. This theory does not tell us why different parts of the universe started expanding simultaneously, why the universe is so flat, homogeneous and isotropic, and what is the origin of galaxies. The existence of these and several other problems of the Big Bang theory forced cosmologists to reconsider its basic assumptions and invent inflationary cosmology.

First versions of inflationary cosmology were complicated and rather problematic. They were based on quantum gravity [1] and on the theory of supercooling during the cosmological phase transitions [2, 3]. However, later it was realized that inflation is a generic regime which may appear in a broad class of theories, without any need for quantum gravity effects and supercooling. The new class of inflationary models was called 'chaotic inflation.' [4]

The simplest version of chaotic inflation is based on the theory of a scalar field ϕ with the potential energy density proportional to ϕ^2 [4]. (One can compare it with electrodynamics where the energy of electric field is proportional to E^2.) Equation of motion of the field ϕ in this model looks like an equation of motion of a harmonic oscillator with friction: The scalar field behaves as a pendulum in a viscous liquid, with viscosity proportional to the speed of expansion of the universe. Because of this term, the scalar field changes very slowly and does not oscillate if the universe expands very fast, but it starts oscillating when the universe slows down.

The main idea of this scenario can be explained as follows: When the energy density of the scalar field was large, the universe was rapidly expanding. At that stage the field did not oscillate and its potential energy density for a long time remained almost constant. Solving Einstein equations for the universe filled with matter with a nearly constant energy density shows that in this regime the universe expanded exponentially fact; it could grow $10^{10000000000}$ times within the first 10^{-30} seconds. This stage is called inflation. Eventually the field ϕ becomes smaller, expansion of the universe slows down, the field starts oscillating, decays, and gives all of its energy to elementary particles created in this process.

Inflation may begin in a domain of a smallest possible size 10^{-33} cm filled by a sufficiently large and homogeneous scalar field with the total mass (energy) smaller than 1 milligram. Then this domain blows up and within 10^{-30} seconds the total energy of the scalar field in this domain becomes much greater than the energy of all particles in the observable part of the universe. We see only a small part of these particles now, because most of them are exponentially far away from us. This 'miracle' happens because the effective pressure of the scalar field is *negative*, so the total energy of matter grows during inflation, $dE = -pdV > 0$.

Inflation is responsible not only for creation of matter in the universe, but also for its large scale structure. Because of inflation, tiny quantum fluctuations of the scalar field were stretched to an exponentially large scale and gave rise to galaxies [5]. In some parts of the universe quantum fluctuations push the scalar field back to its large values. This leads to an eternal process of inflation: the total energy of matter in some of the distant parts of the universe continues growing exponentially even now [6, 7].

In realistic theories of elementary particles there are many different scalar fields, and their potential energy may have many different minima. Recent estimates suggest that in string theory there are more than 10^{100} different minima (different vacuum states) [8]. Even if the evolution of the universe began in a vicinity of one of these minima, quantum fluctuations produced during eternal inflation should bring the scalar fields towards all possible minima in different parts of the universe. After inflation the universe becomes divided into many exponentially large domains where properties of elementary particles and even dimension of space-time may be different. Thus, instead of being a single expanding balloon created in the Big Bang, the universe described by inflationary theory looks like a multiverse, a huge self-reproducing fractal consisting of different parts with different properties [7].

In some of these parts, the value of the vacuum energy is not exactly equal to zero, and the universe may experience an additional late-time stage of acceleration associated with its vacuum energy, or with a slowly changing energy of scalar fields, which is called dark energy. Indeed, recent observations indicate that approximately 5 billion years ago our part of the universe entered a new stage of a very slow acceleration.

Inflationary theory changes in parallel with the development of the theory of elementary particles. Fortunately, its basic predictions are nearly model-independent. For example, in most of the versions of inflationary theory, the universe must be almost exactly flat, and spectrum of perturbations of metric, which are responsible for galaxy formation, should be nearly scale-independent. During the last 15 years, many predictions of inflationary theory have been confirmed by cosmological observations, and this theory gradually became the standard cosmological paradigm. At present, this theory provides the only available mechanism simultaneously explaining creation of energy, matter and the large scale structure of the universe.

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