PHYSICS OF THE EARLY UNIVERSE

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Summary

We review the cosmological standard model, beginning with its foundations in General Relativity and the symmetry assumptions that the Universe at large is homogeneous and isotropic. This standard model describes an expanding Universe and we discuss the observational evidence for it. The rate of expansion is given by the Hubble parameter, whose inverse characterizes the cosmic age. In the early Universe the expansion was much faster than at present. The Universe must have originated in a hot and dense state called the Big Bang. During the first three minutes, it was hot enough to fuse light elements, mainly helium. Atoms formed after approximately 400,000 years. From then on, the heat radiation left over from the Big Bang has propagated freely. It cooled as the Universe expanded. Today we see it as the Cosmic Microwave Background (CMB). The precursors of cosmic structures are seen in the CMB as tiny temperature fluctuations. Much of our knowledge on our Universe at large can be derived from the detailed analysis of these fluctuations.

Only 27% of the energy density of the Universe can be attributed to matter, while 73% are contributed by the unknown dark energy. In turn, 83% of the matter occurs in the

form of unknown dark matter. The initial conditions for the cosmological standard model can be explained by a period of inflationary expansion. This inflationary period can also explain the origin of the tiny temperature fluctuations in the CMB. They originate from primordial quantum fluctuations.

1. Introduction

Why do we believe we could understand the physics of the Universe at all? All of the natural sciences agree on the scientific principle that repeatable experiments under well-defined conditions have to be carried out for understanding their subjects, and that these experiments have to be complemented with a consistent, theoretical foundation that allows ordering the empirical phenomena on the basis of few principles, and predicting new phenomena to be experimentally verified. We cannot experiment with the Universe, its evolution is not repeatable for us, and any attempt at a theoretical understanding necessarily involves enormous extrapolation of our knowledge gained in laboratories on Earth.

Nonetheless, physical cosmology has developed rapidly in less than a century, and it is now not only accepted as a discipline of physics, but also as a driving force behind developments mainly in particle physics and fundamental theoretical concepts. How could this happen? Even in the first half of the 1920s, it was unknown whether the Universe was larger than our home galaxy, the Milky Way. Now, in 2012, we believe we know the global structure of the Universe, we have testable ideas on its origin, and we trust that we know its composition and its age at the per-cent level of precision.

Physical cosmology must be seen as an application of a theory of gravity. Of the four known forces of Nature, two are confined to subatomic scales. Of the remaining two, electromagnetism is shielded at long distances since macroscopic bodies do not carry an appreciable electric charge. Only gravity can act on the huge length scales characteristic of the Universe and its structures.

The currently accepted theory of gravity is Albert Einstein's theory of General Relativity, which was published in its final form on November 25, 1915. Modern physical cosmology rests on this theory, combined with two assumptions purporting the simplicity of the cosmos: It is assumed that we observe the same mean properties of the Universe in all directions around us, and that this would also be found by any other observer in the Universe. Precise observations are now supporting the assumption that the observable Universe is isotropic at large, i.e. it looks the same in all directions. It remains a hypothesis, sometimes called the Copernican Principle, that the same holds true for any position in the Universe. When Alexander Friedman used these assumptions for the first time as a foundation of physical cosmology in 1922, he wrote “it seems to me that no physical or philosophical reasons can be given for” them and that they served “exclusively to simplify the calculations.” By now physicists try to explain them.

Despite their admitted simplicity, the cosmological models that Friedman constructed and that are now named after him form the foundation of modern cosmology. In fact, one might argue that it is precisely their simplicity that made them so successful.

Modern cosmology could turn into one of the cornerstones of the exact physical sciences because nowadays virtually all of a huge variety of observations, reflecting the state of the Universe between 150 seconds after its emergence until now, 14 billion years later, support a unique model of the simple class of Friedman models.

A Universe is called “homogeneous” if it looks, at a given time and on average, the same for all possible observers at arbitrary positions which are imagined to fall freely through the Universe. If a given observer finds, for a fixed distance and in average, the same properties in all directions of the sky the Universe is called “isotropic”. Friedman models are homogeneous and isotropic and they obey Einstein's gravitational field equations.

The homogeneity and isotropy of the Universe allows one to consider measurements of a local property at different positions as being independent measurements of the same quantity. This provides for statistical ensembles similar to ensembles of many repeated laboratory measurements. More precisely, we often can consider observations at a fixed distance from us, but at different angles, as being statistically independent. It is the statistical analysis of huge ensembles that has given birth to what is called today “precision cosmology”.

2. Expansion of the Universe

The presently accepted cosmologies are not static. Space expands with time, as characteristic for generic solutions of Einstein's equations. It was anticipated since approximately 1917, and firmly established by 1930, that galaxies tend to move away from us, and that they do so the faster the farther away they are. The velocities of the galaxies in our cosmological neighborhood increase linearly with their distance: galaxies twice as far away recede twice as fast. A widely used unit of length in cosmology is the so-called Megaparsec, or Mpc for short, which corresponds to 3.26 million light-years. Per Megaparsec distance, the mean recession velocity is now known to increase by 70.4 ± 1.3 kilometers per second. This quantity is called the Hubble parameter.

Apart from the recession of the galaxies, the expansion of the Universe has another important observable effect. In much the same way as the cosmic expansion stretches distances between points in space, say the positions of galaxies, it also stretches the wave-lengths of light. The light that reaches us now from distant sources had to travel for a long time because it travels at a finite speed. It was thus emitted by its sources when the length scales in the Universe were considerably smaller than they are today. Its wave-lengths increased in the same way as all length scales increased. Since red light has a larger wave-length than blue light, this stretching by the cosmic expansion is called cosmological redshift. Some well-observable objects have quite enormous redshifts. Quasars, for example, which are galaxies with extremely luminous cores, can be seen with redshifts approaching ten, indicating that the Universe was about ten times smaller than it is today when these quasars emitted the light that we are now receiving.

Redshifts can be measured by means of lines in spectra. When the light of the Sun is sent through a glass prism or another device splitting light by color into a spectrum like a rainbow, a multitude of dark lines becomes visible. These lines are the fingerprints of chemical elements in the outer gas layers of the Sun, and their appearance and their sequence is as characteristic for the elements as fingerprints are for humans. The expected positions of the lines in the spectrum are defined by the quantum physics of atoms and molecules. If they appear at different positions, the amount can be determined by which they were shifted. Being quite straightforwardly measured, the cosmological redshift is among the most important astronomical diagnostics of the cosmic expansion.

Let us return to the Hubble parameter. Important as its numerical value is, we leave it aside for a moment and focus on the qualitative finding: Galaxies are observed to recede from us the faster the farther they are. We see them recede in the same manner into all directions. This is exactly the behavior expected in Friedman models (apart from exceptional cases). These models are necessarily unstable, they have to expand or contract, and if they expand, an imaginary observer immersed into them would see precisely the type of recession that we observe. In fact, it was recognized by Georges Lemaître already in 1927 that the recession of the galaxies might indicate the expansion behavior predicted by Friedman's cosmological models constructed within General Relativity.

However, the numerical value of the Hubble parameter is fundamentally significant in its own right. Since the Universe is now observed to expand, it should contract going into the past. If the expansion velocity remained the same throughout the history of the Universe, which may be an acceptable assumption for an estimate, a time scale for the existence of the Universe is set simply by the reciprocal value of the Hubble parameter, which turns out to be 14 billion years. Does this tentative age of the Universe agree with the ages of the objects it is populated by?

It does: Chronology with the help of long-lived radioactive elements such as uranium reveal that the Earth is 4.2 billion years old. The oldest objects in our Galaxy, which are white dwarfs and globular clusters, formed between 10 and 13 billion years ago. Even though the age determinations of astronomical objects are in part quite uncertain, it is important that we can be assured that the Universe seems to be just a bit older than its oldest inhabitants, but not younger.

Actually, the Hubble parameter changes in the course of the cosmological evolution, but the order of magnitude estimate of the age of the Universe remains the same. Today the time elapsed since the Big Bang is measured (see later) to be 13.7 billion years.

3. Primordial Hot Plasma

Since the recession of the galaxies indicates that the Universe as a whole expands, it was smaller a billion years ago than it is today. As we keep going into the past, does the Universe keep shrinking? At first sight, one would clearly expect this. Gravity should slow down the motion of massive objects simply because they attract each other. The expansion rate of the Universe should thus have been even larger in the past than it is today. Cosmologists having observed the Universe during earlier epochs of cosmic history should have measured a larger Hubble parameter. A finite time ago, all distances between the objects we see today must have been very small, and the Universe must have developed from a very dense initial state. Without precise and detailed knowledge of the physical state of all forms of matter, energy and the Universe itself, we call this extremely dense initial state the Big Bang. This purposefully derogatory term was coined by Fred Hoyle, who criticized the idea of a cosmological beginning and proposed an alternative cosmological model with Herman Bondi and Thomas Gold, called the Steady-State model. Conceptually attractive as it was, the Steady-State model received a severe blow when it was discovered that radio galaxies evolve, and a fatal blow when the Cosmic Microwave Background was discovered; see below.

Following Einstein's equations for gravity, a Universe with the observed matter and radiation that is nowadays expanding should have originated in a Big Bang a finite time ago. In principle, one could imagine models which avoid a Big Bang. Such Friedman models would first be in a shrinking state, then reach a minimum size before they start a phase of expansion. Can we rule out living in a Universe of this sort?

With three simple observational facts, we can establish that the Universe was once in a very hot and dense state. These facts are: (1) Quasars are being seen with redshifts exceeding four. When they emitted the light that we now observe, length scales in the Universe were smaller than 0.2 times than they are today. (2) There is a certain minimum amount of matter in the Universe. This is at least as much as is needed for producing the light we can observe, but probably substantially more because by far the majority of the cosmic matter is not in a condition to produce any light. (3) There is radiation in the Universe whose energy density is dominated by the Cosmic Microwave Background that we will have to discuss below in detail. These observations provide sufficient information about the composition of the Universe in order to conclude that, if our Universe can with reasonable approximation be described by a Friedman model at all, then it must have originated from a Big Bang. If we wish to stay within the framework of the Friedman models, we thus have to accept that the Universe emerged from an extremely dense beginning a finite time ago. For the types of matter and radiation we know, extremely dense also means extremely hot. As we can extrapolate from everyday life, compressing a gas makes it heat up. We expect the same to have happened in the Universe: If it had a dense beginning, it should have had a hot beginning.

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Biographical Sketches

Christof Wetterich studied physics in Paris, Cologne and Freiburg from 1972 to 1978. He received his diploma in 1978 from Freiburg University and remained employed there until 1981, first as a doctoral student until 1979, then as a post-doc. He was a Fellow at CERN, Geneva, from 1981 to 1983 and obtained his habilitation at Freiburg University in 1983. After a post-doc at Bern University between 1983 and 1985, he briefly returned to CERN with a Heisenberg Fellowship, but moved on to a permanent staff position at DESY, Hamburg, which he held from 1985 to 1992. He was appointed as a professor of theoretical physics at Heidelberg University in 1992, where he remained since. From 1999 to 2000, he was the Dean of the department of physics and astronomy at Heidelberg University. He was awarded with the Max Planck Research Prize in 2005, became an external member of the Max Planck Institute for Nuclear Physics and the Academy of Sciences in Heidelberg in 2006, and received an Advanced Grant for his work on functional renormalization from the European Research Council in 2012. He is well known for his many fundamental contributions to almost all areas of theoretical physics, ranging from cosmology to non-equilibrium quantum field theory and to quantum gravity.

Matthias Bartelmann studied physics at the Ludwig-Maximilians University (LMU) in Munich from 1985 to 1990. For his diploma thesis, he moved to the Max Planck Institute for Astrophysics (MPA) in Garching. Having received his diploma in 1990, he remained there as a doctoral student and received his PhD from LMU in 1992. From 1992 until 1998, he was a post-doc first at MPA, then at the Harvard-Smithsonian Center for Astrophysics from 1994 to 1995, then again at MPA, where he became a staff member in 1998. From 1997 to 2003, he was responsible for the German contribution to the Planck satellite project. He received his habilitation in 1998 and became lecturer at LMU in 2000. Since 2003, he has been professor for theoretical astrophysics at Heidelberg University. He was the Dean of the department for physics and astronomy at Heidelberg University from 2006 to 2008. In 2012, he was elected as a board member of the German Physical Society. He received the Otto Hahn Medal of the Max Planck Society for his doctoral dissertation, the Ludwig Biermann Prize of the German Astronomical Society in 1996 and a Heisenberg stipend of the German Science Foundation in 1998. He is interested in theoretical astrophysics and cosmology and mostly works on gravitational lensing and cosmological structure formation.