

THE EVOLUTION OF THE UNIVERSE

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With the recent measurements of temperature and polarization anisotropies in the microwave background by WMAP, we have entered a new era of precision cosmology, with the cosmological parameters of a Standard Cosmological Model determined to 1%. This Standard Model is based on the Big Bang theory and the inflationary paradigm, a period of exponential expansion in the early universe responsible for the large-scale homogeneity and spatial flatness of our observable patch of the Universe. The spectrum of metric perturbations, seen in the microwave background as temperature anisotropies, were produced during inflation from quantum fluctuations that were stretched to cosmological size by the expansion, and later gave rise, via gravitational collapse, to the observed large-scale structure of clusters and superclusters of galaxies. Furthermore, the same theory predicts that all the matter and radiation in the universe today originated at the end of inflation from an explosive production of particles that could also have been the origin of the present baryon asymmetry, before the universe reached thermal equilibrium at a very large temperature. From there on, the universe cooled down as it expanded, in the way described by the standard hot Big Bang model.

1 Introduction

Our present understanding of the universe is based upon the successful hot Big Bang theory, which explains its evolution from the first fraction of a second to our present age, around 13 billion years later. This theory rests upon four strong pillars, a theoretical framework based on general relativity, as put forward by Albert Einstein and Alexander A. Friedmann in the 1920s, and three strong observational facts. First, the expansion of the universe, discovered by Edwin P. Hubble in the 1930s, as a recession of galaxies at a speed proportional to their distance from us. Second, the relative abundance of light elements, explained by George Gamow in the 1940s, mainly that of helium, deuterium and lithium, which were cooked from the nuclear reactions that took place at around a second to a few minutes after the Big Bang, when the universe was a hundred times hotter than the core of the sun. Third, the cosmic microwave background (CMB), the afterglow of the Big Bang, discovered in 1965 by Arno A. Penzias and Robert W. Wilson as a very isotropic blackbody radiation at a temperature of about 3 degrees Kelvin, emitted when the universe was cold enough to form neutral atoms, and photons decoupled from matter, 380 000 years after the Big Bang. Today, these observations are confirmed to within a few percent accuracy, and have helped establish the hot Big Bang as the preferred model of the universe.

The Big Bang theory could not explain, however, the origin of matter and structure in the universe; that is, the origin of the matter–antimatter asymmetry, without which the universe today would be filled by a uniform radiation continuously expanding and cooling, with no traces of matter, and thus without the possibility to form gravitationally bound systems like galaxies, stars and planets that could sustain life. Moreover, the standard Big Bang theory assumes, but cannot explain,

the origin of the extraordinary smoothness and flatness of the universe on the very large scales seen by the microwave background probes and the largest galaxy catalogs. It can neither explain the origin of the primordial density perturbations that gave rise, via gravitational collapse, to cosmic structures like galaxies, clusters and superclusters; nor the nature of the dark matter and dark energy that we believe permeates the universe; nor the origin of the Big Bang itself.

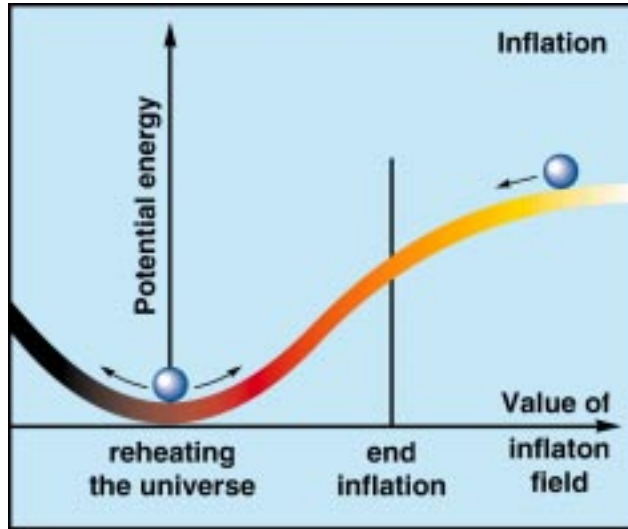


Figure 1. The inflaton field can be represented as a ball rolling down a hill. During inflation, the energy density is approximately constant, driving the tremendous expansion of the universe. When the ball starts to oscillate around the bottom of the hill, inflation ends and the inflaton energy decays into particles. In certain cases, the coherent oscillations of the inflaton could generate a resonant production of particles which soon thermalize, reheating the universe.

In the 1980s, a new paradigm, deeply rooted in fundamental physics, was put forward by Alan H. Guth, Andrei D. Linde and others, to address these fundamental questions. According to the inflationary paradigm, the early universe went through a period of exponential expansion, driven by the approximately constant energy density of a scalar field called the inflaton. In modern physics, elementary particles are represented by quantum fields, i.e. a function of space and time whose quantum oscillations can be interpreted as particles. For instance, the photon is the particle associated with the electromagnetic field. In our case, the inflaton field has, associated with it, a large potential energy density, which drives the exponential expansion during inflation, see Fig. 1. We know from general relativity that the density of matter determines the expansion of the universe, but a constant energy density acts in a very peculiar way: as a repulsive force that makes any two points in space separate at exponentially large speeds. (This does not violate the laws of causality because there is no information carried along in the expansion, it is simply the stretching of space-time.)

This superluminal expansion is capable of explaining the large scale homogeneity of our observable universe and, in particular, why the microwave background looks so isotropic: regions separated today by more than 1° in the sky were, in fact, in causal contact before inflation, but were stretched to cosmological distances by the expansion, see Fig. 2. Any inhomogeneities present before the tremendous expansion would be washed out. Moreover, in the usual Big Bang scenario a flat universe, one in which the gravitational attraction of matter is exactly balanced by the cosmic expansion, is unstable under perturbations: a small deviation from flatness is amplified and soon produces either an empty universe or a collapsed one. For the universe to be nearly flat today, it must have been extremely flat at nucleosynthesis for example, deviations not exceeding more than one part in 10^{15} . This extreme fine tuning of initial conditions was also solved by the inflationary paradigm, see Fig. 3. Thus inflation is an extremely elegant hypothesis that explains how a region much, much greater than our own observable universe could have become smooth and flat without recourse to *ad hoc* initial conditions.

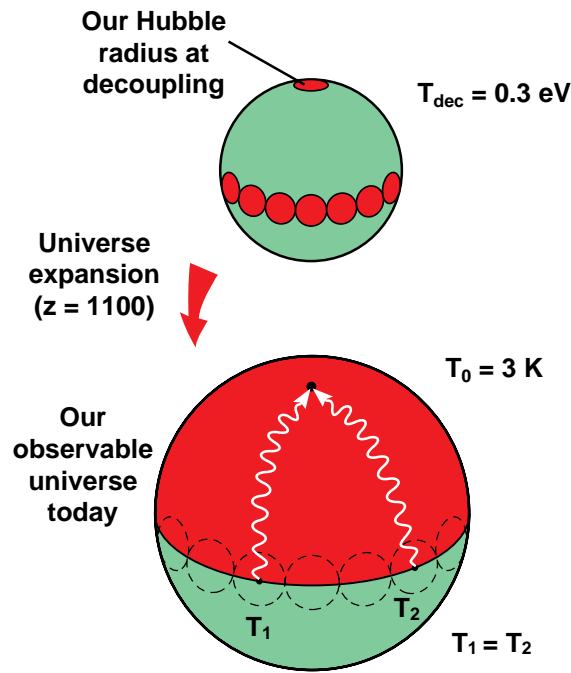


Figure 2. Perhaps the most acute problem of the Big Bang model is explaining the extraordinary homogeneity and isotropy of the microwave background. Information cannot travel faster than the speed of light, so the causal region (so-called horizon or Hubble radius) at the time of photon decoupling could not be larger than 300 000 light years across, or about 1° projected in the sky today. So why should regions that are separated by more than 1° in the sky have the same temperature, when the photons that come from those two distant regions could not have been in causal contact when they were emitted? This constitutes the so-called horizon problem, which is spectacularly solved by inflation.

2 The origin of structure in the universe

If cosmological inflation made the universe so extremely flat and homogeneous, where did the galaxies and clusters of galaxies come from? One of the most astonishing predictions of inflation, one that was not even expected, is that quantum fluctuations of the inflaton field are stretched by the exponential expansion and generate large-scale perturbations in the metric. Inflaton fluctuations are small wave packets of energy that, according to general relativity, modify the space-time fabric, creating a whole spectrum of curvature perturbations. The use of the word spectrum here is closely related to the case of light waves propagating in a medium: a spectrum characterizes the amplitude of each given wavelength. In the case of inflation, the inflaton fluctuations induce waves in the space-time metric that can be decomposed into different wavelengths, all with approximately the same amplitude, that is, corresponding to a scale-invariant spectrum. These patterns of perturbations in the metric are like fingerprints that unequivocally characterize a period of inflation. When matter fell in the troughs of these waves, it created density perturbations that collapsed gravitationally to form galaxies, clusters and superclusters of galaxies, with a spectrum that is also scale invariant. Such a type of spectrum was proposed in the early 1970s (before inflation) by Edward R. Harrison, and independently by the Russian cosmologist Yakov B. Zel'dovich, to explain the distribution of galaxies and clusters of galaxies on very large scales in our observable universe.

Various telescopes – like the Hubble Space Telescope, the twin Keck telescopes in Hawaii and the European Southern Observatory telescopes in Chile – are exploring the most distant regions of the universe and discovering the first galaxies at large distances. According to the Big Bang theory, the further the galaxy is, the larger its recession velocity, and the larger the shift towards the red of the spectrum of light from that galaxy. Astronomers thus measure distances in units of red-shift z . The furthest galaxies observed so far are at redshifts of $z \simeq 7$, or 13 billion light years from the Earth, whose light was emitted when the universe had only about 2% of its present age. Only a few galaxies are known at those redshifts, but there are at present various catalogs like the IRAS PSCz and Las Campanas redshift survey, that study the spatial distribution of hundreds of thousands of galaxies up to distances of a billion light years, or $z < 0.1$, that recede from us at speeds of tens of thousands of kilometres per second. These catalogs are telling us about the evolution of clusters of galaxies in the universe, and already put constraints on the theory of structure formation based on the gravitational collapse of the small inhomogeneities produced during inflation. From these observations one can infer that most galaxies formed at redshifts of the order of 2 – 4; clusters of galaxies formed at redshifts of order 1, and superclusters are forming now. That is, cosmic structure formed from the bottom up: from galaxies to clusters to superclusters, and not the other way around.

This fundamental difference is an indication of the type of matter that gave rise to structure. We know from primordial nucleosynthesis that all the baryons in the universe cannot account for the observed amount of matter, so there must be some extra matter (dark since we don't see it) to account for its gravitational pull. Whether it is relativistic (hot) or non-relativistic (cold) could be inferred

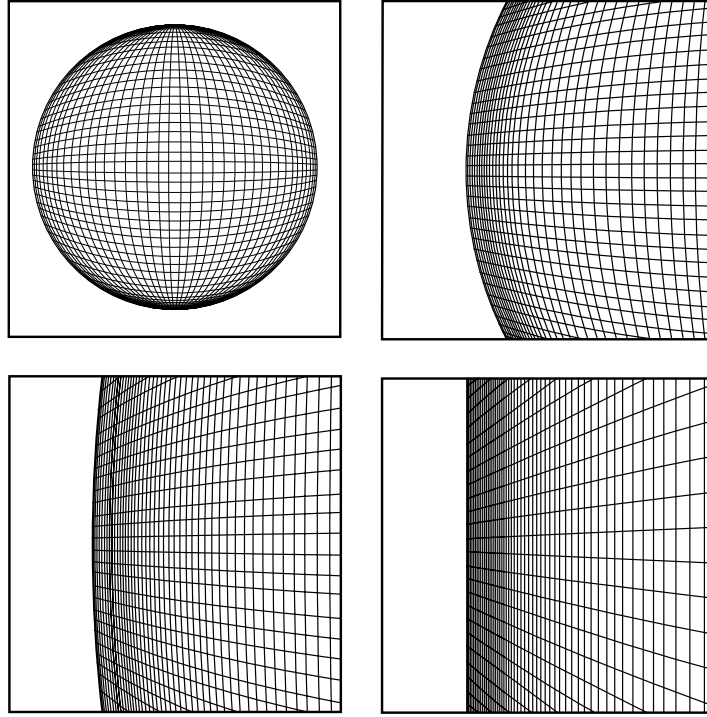


Figure 3. The exponential expansion during inflation made the radius of curvature of the universe so large that our observable patch of the universe today appears essentially flat, analogous (in three dimensions) to how the surface of a balloon appears flatter and flatter as we inflate it to enormous sizes. This is a crucial prediction of cosmological inflation that will be tested to extraordinary accuracy in the next few years.

from observations: relativistic particles tend to diffuse from one concentration of matter to another, thus transferring energy among them and preventing the growth of structure on small scales. This is excluded by observations, so we conclude that most of the matter responsible for structure formation must be cold. How much there is is a matter of debate at the moment. Some recent analyses suggest that there is not enough cold dark matter to reach the critical density required to make the universe flat. If we want to make sense of the present observations, we must conclude that some other form of energy permeates the universe. In order to resolve this issue, even deeper galaxy redshift catalogs are underway, looking at millions of galaxies, like the Sloan Digital Sky Survey (SDSS) and the Anglo-Australian two degree field Galaxy Redshift Survey, which are at this moment taking data, up to redshifts of $z < 3$, or several hundred billion light years away, over a large region of the sky. These important observations will help astronomers determine the nature of the dark matter and test the validity of the models of structure formation.

However, if galaxies did indeed form from gravitational collapse of density per-

Table 1. **The parameters of the standard cosmological model.** The standard model of cosmology has about 20 different parameters, needed to describe the background space-time, the matter content and the spectrum of metric perturbations. We include here the present range of the most relevant parameters (with 1σ errors), as recently determined by MAP, and the error with which the Planck satellite will be able to determine them in the near future. The rate of expansion is written in units of $H = 100 h$ km/s/Mpc

physical quantity	symbol	MAP	Planck
total density	Ω_0	1.02 ± 0.02	0.7%
baryonic matter	Ω_B	0.044 ± 0.004	0.6%
cosmological constant	Ω_Λ	0.73 ± 0.04	0.5%
cold dark matter	Ω_M	0.23 ± 0.04	0.6%
hot dark matter	$\Omega_\nu h^2$	< 0.0076 (95% c.l.)	1%
sum of neutrino masses	$\sum m_\nu$ (eV)	< 0.23 (95% c.l.)	1%
CMB temperature	T_0 (K)	2.725 ± 0.002	0.1%
baryon to photon ratio	$\eta \times 10^{10}$	6.1 ± 0.3	0.5%
baryon to matter ratio	Ω_B/Ω_M	0.17 ± 0.01	1%
spatial curvature	Ω_K	< 0.02 (95% c.l.)	0.5%
rate of expansion	h	0.71 ± 0.03	0.8%
age of the universe	t_0 (Gyr)	13.7 ± 0.2	0.1%
age at decoupling	t_{dec} (kyr)	379 ± 8	0.5%
age at reionization	t_r (Myr)	180 ± 100	5%
spectral amplitude	A	0.833 ± 0.085	0.1%
spectral tilt (at $k_0 = 0.05 \text{ Mpc}^{-1}$)	n_s	0.93 ± 0.03	0.2%
spectral tilt variation	$dn_s/d\ln k$	-0.031 ± 0.017	0.5%
tensor-scalar ratio	r	< 0.71 (95% c.l.)	5%
reionization optical depth	τ	0.17 ± 0.04	5%
redshift of matter-energy equality	z_{eq}	3233 ± 200	5%
redshift of decoupling	z_{dec}	1089 ± 1	0.1%
width of decoupling	Δz_{dec}	195 ± 2	1%
redshift of reionization	z_r	20 ± 10	2%

turbations produced during inflation, one should also expect to see such ripples in the metric as temperature anisotropies in the cosmic microwave background, that is, minute deviations in the temperature of the blackbody spectrum when we look at different directions in the sky. Such anisotropies had been looked for ever since Penzias and Wilson's discovery of the CMB, but had eluded all detection, until NASA's Cosmic Background Explorer (COBE) satellite discovered them in 1992. The reason why they took so long to be discovered was that they appear as perturbations in temperature of only one part in 100 000. There is, in fact, a dipolar anisotropy of one part in 1000, in the direction of the Virgo cluster, but that is interpreted consistently as our relative motion with respect to the microwave background due to the local distribution of mass, which attracts us gravitationally towards the Virgo cluster. When subtracted, we are left with a whole spectrum of anisotropies in the higher multipoles (quadrupole, octopole, etc.), see Fig. 4. Soon after COBE,

other groups quickly confirmed the detection of temperature anisotropies at around $30\ \mu\text{K}$, at higher multipole numbers or smaller angular scales.

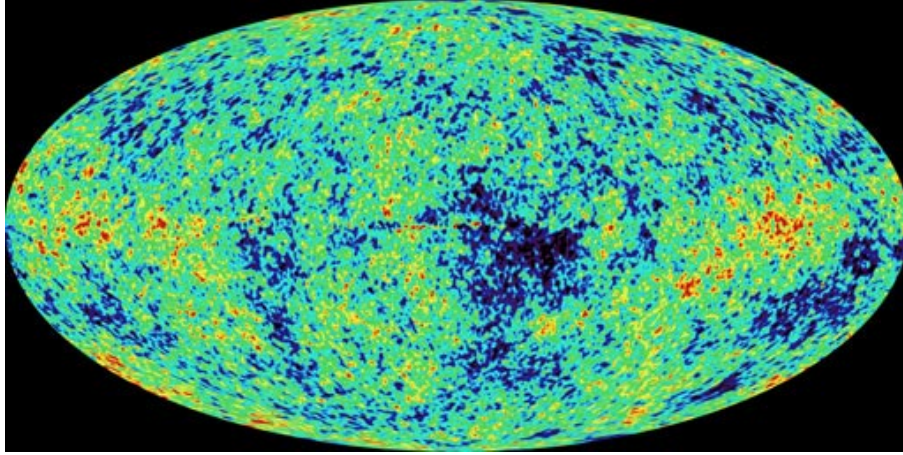


Figure 4. The microwave background sky as seen by WMAP, with 10 arc minute resolution. It shows the intrinsic CMB anisotropies, corresponding to the quadrupole and higher multipoles, at the level of a few parts in 10^5 . The galaxy is a foreground and has been subtracted.

There are at this moment dozens of ground and balloon-borne experiments analysing the anisotropies in the microwave background with angular resolutions from 7° to a few arc minutes in the sky. The physics of the CMB anisotropies is relatively simple: photons scatter off charged particles (protons and electrons), and carry energy, so they feel the gravitational potential associated with the perturbations imprinted in the metric during inflation. An overdensity of baryons (protons and neutrons) does not collapse under the effect of gravity until it enters the causal Hubble radius. The perturbation continues to grow until radiation pressure opposes gravity and sets up acoustic oscillations in the plasma, very similar to sound waves. Since overdensities of the same size will enter the Hubble radius at the same time, they will oscillate in phase. Moreover, since photons scatter off these baryons, the acoustic oscillations occur also in the photon field and induces a pattern of peaks in the temperature anisotropies in the sky, at different angular scales, see Fig. 5. The larger the amount of baryons, the higher the peaks. The first peak in the photon distribution corresponds to overdensities that have undergone half an oscillation, that is, a compression, and appear at a scale associated with the size of the sonic horizon at last scattering (when the photons decoupled) or about 1° in the sky. Other peaks occur at harmonics of this, corresponding to smaller angular scales. Since the amplitude and position of the primary and secondary peaks are directly determined by the sound speed (and, hence, the equation of state) and by the geometry and expansion of the universe, they can be used as a powerful test of the density of baryons and dark matter, and other cosmological parameters.

By looking at these patterns in the anisotropies of the microwave background,

cosmologists can determine not only the cosmological parameters but also the primordial spectrum of metric perturbations produced during inflation. It turns out that the observed temperature anisotropies are compatible with a scale-invariant spectrum, as predicted by inflation. This is remarkable, and gives very strong support to the idea that inflation may indeed be responsible for both the CMB anisotropies and the large-scale structure of the universe. Different models of inflation have different specific predictions for the fine details associated with the spectrum generated during inflation. It is these minute differences that will allow cosmologists to differentiate between alternative models of inflation and discard those that do not agree with observations. However, most importantly, perhaps, the pattern of anisotropies predicted by inflation is completely different from those predicted by alternative models of structure formation, like cosmic defects: strings, vortices, textures, etc. These are complicated networks of energy density concentrations left over from an early universe phase transition, analogous to the defects formed in the laboratory in certain kinds of liquid crystals when they go through a phase transition. The cosmological defects have spectral properties very different from those generated by inflation. That is why it is so important to launch more sensitive instruments, and with better angular resolution, to determine the properties of the CMB temperature and polarization anisotropies. With the recent observations of these anisotropies by the Microwave Anisotropy Probe (MAP) satellite, launched by NASA in 2000, we can now discard topological defects as the source of structure in the universe at more than ten standard deviations. The full sky coverage of MAP and its extraordinary angular resolution (10 arcminutes) allows cosmologists to determine today a handful of cosmological parameters at the 1% level, see table 1. We have thus entered the era of precision cosmology and we can now speak of a truly Standard Model of Cosmology.

In the next few years, a third generation satellite – the Planck Surveyor, due to be launched by the European Space Agency in 2007 – will measure those temperature anisotropies with 10 times better angular resolution and 10 times better sensitivity than MAP, and thus allow cosmologists to determine the parameters of the standard cosmological model with 1 per mil accuracy. What makes the microwave background observations particularly powerful is the absence of large systematic errors that plague other cosmological measurements. As we have discussed above, the physics of the microwave background is relatively simple, compared to, say, the physics of supernova explosions, and computations can be done consistently within perturbation theory. Thus, most of the systematic errors are theoretical in nature, due to our ignorance about the primordial spectrum of metric perturbations from inflation. There is a great effort at the moment in trying to cover a large region in the parameter space of models of inflation, to ensure that we have considered all possible alternatives, like isocurvature or pressure perturbations, non scale invariant or tilted spectra and non-Gaussian density perturbations.

In particular, inflation also predicts a spectrum of gravitational waves. Their amplitude is directly proportional to the total energy density during inflation, and thus its detection would immediately tell us about the energy scale (and, therefore, the epoch in the early universe) at which inflation occurred. If the period of inflation responsible for the observed CMB anisotropies is associated with the Grand

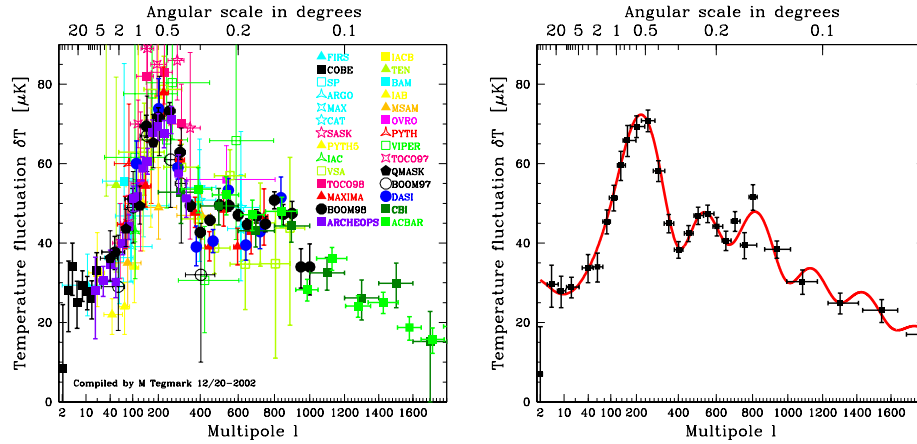


Figure 5. There are at present about thirty experiments (in satellites, from the ground and balloon-borne) looking at the microwave background temperature anisotropies with angular resolutions from 7° to a few arc minutes in the sky, corresponding to multipole numbers $l = 2 - 3000$. The right panel shows the l -binned spectrum. Present observations suggest the existence of a series of acoustic peaks in the angular distribution, as predicted by inflation. The theoretical curve (red thick line) illustrates the concordance Λ -CDM model which fits the data.

Unification scale, 12 orders of magnitude above the electroweak scale, when the strong and electroweak interactions are supposed to unify, then there is a chance that we might see the effect of gravitational waves in the future satellite measurements, specially from the analysis of polarization anisotropies in the microwave background maps.

Moreover, the stochastic background of gravitational waves generated during inflation could eventually be observed by ground-based laser interferometers like LIGO and VIRGO, which will start taking data as gravitational wave observatories in the next few years. These are extremely sensitive devices that could distinguish minute spatial variations, of one part in 10^{23} or better, induced when a gravitational wave from a distant source passes through the Earth and distorts the space-time metric. Gravitational waves moving at the speed of light are a fundamental prediction of general relativity. Their existence was indirectly confirmed by Russell A. Hulse and Joseph H. Taylor, through the precise observations of the decay in the orbital period of the pulsar PSR1913+16, due to the emission of gravitational radiation. In the near future, observations of gravitational waves with laser interferometers will open a completely new window into the universe. It will allow us to observe with a very different probe (that of the gravitational interaction) a huge range of phenomena, from the most violent processes in our galaxy and beyond, like supernova explosions, neutron star collisions, quasars, gamma ray bursts, etc., to the origin of the universe. Moreover, NASA and ESA have joined efforts to construct LISA, an interferometer in space, with satellites millions of kilometers apart, whose sensitivity is good enough to detect the minutest perturbations in space-time induced by the stochastic background of gravitational waves coming from inflation.

In our quest for the parameters of the standard cosmological model, various

groups are searching for distant astrophysical objects that can serve as standard candles to determine the distance to the object from their observed apparent luminosity. A candidate that has recently been exploited with great success is a certain type of supernova explosions at large redshifts. These are stars at the end of their life cycle that become unstable and violently explode in a natural thermonuclear explosion that out-shines their progenitor galaxy. The intensity of the distant flash varies in time, it takes about three weeks to reach its maximum brightness and then it declines over a period of months. Although the maximum luminosity varies from one supernova to another, depending on their original mass, their environment, etc., there is a pattern: brighter explosions last longer than fainter ones. By studying the light curves of a reasonably large statistical sample, cosmologists from two competing groups, the Supernova Cosmology Project and the High-redshift Supernova Project, are confident that they can use this type of supernova as a standard candle. Since the light coming from some of these rare explosions has travelled for a large fraction of the size of the universe, one expects to be able to infer from their distribution the spatial curvature and the rate of expansion of the universe. One of the surprises revealed by these observations is that the universe appears to be accelerating instead of decelerating, as was expected from the general attraction of matter; something seems to be acting as a repulsive force on very large scales. The most natural explanation for this is the existence of a cosmological constant, a diffuse vacuum energy that permeates all space and, as explained above, gives the universe an acceleration that tends to separate gravitationally bound systems from each other. The origin of such a vacuum energy is one of the biggest problems of modern physics. Its observed value is 120 orders of magnitude smaller than predicted by quantum mechanics. If confirmed, it will pose a real challenge to theoretical physics, one that may affect its most basic foundations.

3 The origin of matter in the universe

Cosmological inflation may be responsible for the metric perturbations that later gave rise to the large scale structures we see in the universe, but where did all the matter in the universe come from? Why isn't all the energy in photons, which would have inevitably redshifted away in a cold universe devoid of life? How did we end up being matter dominated? Everything we see in the universe, from planets and stars, to galaxies and clusters of galaxies, is made out of matter, so where did the antimatter in the universe go? Is this the result of an accident, a happy chance occurrence during the evolution of the universe, or is it an inevitable consequence of some asymmetry in the laws of nature? Theorists believe that the excess of matter over antimatter comes from fundamental differences in their interactions soon after the end of inflation.

Inflation is an extremely efficient mechanism in diluting any particle species or fluctuations. At the end of inflation, the universe is empty and extremely cold, dominated by the homogeneous coherent mode of the inflaton. Its potential energy density is converted into particles, as the inflaton field oscillates coherently around the minimum of its potential, see Fig 1. These particles are initially very far from equilibrium, but they strongly interact among themselves and soon reach thermal

equilibrium at a very large temperature. From there on, the universe expanded isentropically, cooling down as it expanded, in the way described by the standard hot Big Bang model. Thus the origin of the Big Bang itself, and the matter and energy we observe in the universe today, can be traced back to the epoch in which the inflaton energy density decayed into particles. Such a process is called reheating of the universe.

Recent developments in the theory of reheating suggest that the decay of the inflaton energy could be explosive due to the coherent oscillations of the inflaton, which induce its stimulated decay. The result is a resonant production of particles in just a few inflaton oscillations, an effect very similar to the stimulated emission of a laser beam of photons. The number of particles produced this way is exponentially large, which may explain the extraordinarily large entropy, of order 10^{89} particles, in our observable patch of the universe today. However, the inflaton is supposed to be a neutral scalar field, and thus its interactions cannot differentiate between particles and antiparticles. How did we end up with more matter than antimatter? The study of this cosmological asymmetry goes by the name of baryogenesis since baryons (mainly protons and neutrons) are the fundamental constituents of matter in planets, stars and galaxies in the universe today. So, what are the conditions for baryogenesis?

Everything we know about the properties of elementary particles is included in the standard model of particle physics. It describes more than 100 observed particles and their interactions in terms of a few fundamental constituents: six quarks and six leptons, and their antiparticles. The standard model describes three types of interactions: the electromagnetic force, the strong and the weak nuclear forces. These forces are transmitted by the corresponding particles: the photon, the gluon and the W and Z bosons. The theory also requires a scalar particle, the Higgs particle, responsible for the masses of quarks and leptons and the breaking of the electroweak symmetry at an energy scale 1000 times the mass of the proton. The Higgs is believed to lie behind most of the mysteries of the standard model, including possibly also the asymmetry between matter and antimatter.

In 1967, the Russian physicist Andrei Sakharov pointed out the three necessary conditions for the baryon asymmetry of the universe to develop. First, we need interactions that do not conserve baryon number B, otherwise no asymmetry could be produced in the first place. Second, C and CP symmetry must be violated, in order to differentiate between matter and antimatter, otherwise B non-conserving interactions would produce baryons and antibaryons at the same rate, thus maintaining zero net baryon number. Third, these processes should occur out of thermal equilibrium, otherwise particles and antiparticles would be produced at the same rate. The standard model is baryon symmetric at the classical level, but violates B at the quantum level, through the chiral anomaly. Electroweak interactions violate C and CP, but the magnitude of the latter is clearly insufficient to account for the observed baryon asymmetry. This failure suggests that there must be other sources of CP violation in nature, and thus the standard model of particle physics is probably incomplete.

One of the most popular extensions of the standard model includes a new symmetry called supersymmetry, which relates bosons (particles that mediate inter-

actions) with fermions (the constituents of matter). Those extensions generically predict other sources of CP violation coming from new interactions at scales above 1000 times the mass of the proton. Such scales will soon be explored by particle colliders like the Large Hadron Collider (LHC) at CERN (the European Centre for Particle Physics) and by the Tevatron at Fermilab. The mechanism for baryon production in the early universe in these models relies on the strength of the electroweak phase transition, as the universe cooled and the symmetry was broken. Only for strongly first-order phase transitions is the universe sufficiently far from equilibrium to produce enough baryon asymmetry. Unfortunately, the phase transition in these models is typically too weak to account for the observed asymmetry, so some other mechanism is needed.

If reheating after inflation occurred in an explosive way, via the resonant production of particles from the inflaton decay, as recent developments suggest, then the universe has actually gone through a very non-linear, non-perturbative and very far from equilibrium stage, before thermalizing via particle interactions. Electroweak baryogenesis could then take place during that epoch, soon after the end of low energy inflation at the electroweak scale. Such models can be constructed but require a specially flat direction (a very small mass for the inflaton) during inflation, in order to satisfy the constraints from the amplitude of temperature anisotropies seen by COBE. Such flat directions are generic in supersymmetric extensions of the standard model. After inflation, the inflaton acquires a large mass from its interaction with the Higgs field.

The crucial ingredient of departure from equilibrium, necessary for the excess production of baryons over antibaryons, is strongly present in this new scenario of baryogenesis, as the universe develops from a zero-temperature and zero-entropy state, at the end of inflation, to a thermal state with exponentially large numbers of particles, the origin of the standard hot Big Bang. If, during this stage, fundamental or effective interactions that are B, C and CP violating were fast enough compared to the rate of expansion, the universe could have ended with the observed baryon asymmetry of one part in 10^{10} , or one baryon per 10^9 photons today, as deduced from observations of the light element abundances. Recent calculations suggest that indeed, the required asymmetry could be produced as long as some new physics, just above the electroweak symmetry breaking scale, induces a new effective CP violating interaction.

These new phenomena necessarily involve an interaction between the Higgs particle, responsible for the electroweak symmetry breaking, and the inflaton field, responsible for the period of cosmological inflation. Therefore, for this scenario to work, it is expected that both the Higgs and the inflaton particles be discovered at the future particle physics colliders like the LHC and the Next Linear Collider (NLC). Furthermore, this new physics would necessarily involve new interactions in the quark sector, for example inducing CP violations in the B meson (a bound state composed of a bottom quark and an antidown quark) system. Such violations are the main research objective of the B factory at SLAC in California and at KEK, the High Energy Accelerator Research Organization in Tsukuba, Japan. These experiments have already been collecting data for a couple years, and for the moment are in perfect agreement with the Standard Model of particle physics.

However, perhaps in the near future they may detect a deviation which could give us a clue to the origin of CP, and thus to the matter–antimatter asymmetry of the Universe and, possibly, to baryogenesis from reheating after inflation.

4 Conclusions

We have entered a new era in cosmology, where a host of high-precision measurements are already posing challenges to our understanding of the universe: the density of ordinary matter and the total amount of energy in the universe; the microwave background anisotropies on a fine-scale resolution; primordial deuterium abundance from quasar absorption lines; the acceleration parameter of the universe from high-redshift supernovae observations; the rate of expansion from gravitational lensing; large scale structure measurements of the distribution of galaxies and their evolution; and many more, which already put constraints on the parameter space of cosmological models. However, these are only the forerunners of the precision era in cosmology that will dominate this millennium, and will make cosmology a science in its own right.

It is important to bear in mind that all physical theories are approximations of reality that can fail if pushed too far. Physical science advances by incorporating earlier theories that are experimentally supported into larger, more encompassing frameworks. The standard Big Bang theory is supported by a wealth of evidence, nobody really doubts its validity anymore. However, in the last decade it has been incorporated into the larger picture of cosmological inflation, which has become the new standard cosmological model. All cosmological issues are now formulated in the context of the inflationary paradigm. It is the best explanation we have at the moment for the increasing set of cosmological observations.

In the next few years we will have an even larger set of high-quality observations that will test inflation and the cold dark matter paradigm of structure formation, and determine most of the 20 or more parameters of the standard cosmological model to a few per mil accuracy, see Table 1. It may seem that with such a large number of parameters one can fit almost anything. However, that is not the case when there is enough quantity and quality of data. An illustrative example is the standard model of particle physics, with around 21 parameters and a host of precise measurements from particle accelerators all over the world. This model is, nowadays, rigorously tested, and its parameters measured to a precision of better than 1% in most cases. It is clear that high-precision measurements will make the standard model of cosmology as robust as that of particle physics. This is definitely a very healthy field, but there is still a lot to do. With the advent of better and larger precision experiments, cosmology is becoming a mature science, where speculation has given way to phenomenology.

However, there are still many unanswered fundamental questions in this emerging picture of cosmology. For instance, we still do not know the nature of the inflaton field, is it some new fundamental scalar field in the electroweak symmetry breaking sector, or is it just some effective description of a more fundamental high energy interaction? Hopefully, in the near future, experiments in particle physics might give us a clue to its nature. Inflation had its original inspiration in the Higgs

field, the scalar field supposed to be responsible for the masses of elementary particles (quarks and leptons) and the breaking of the electroweak symmetry. Such a field has not been found yet, and its discovery at the future particle colliders may help understand one of the truly fundamental problems in physics, the origin of masses. If the experiments discover something completely new and unexpected, it would automatically affect inflation at a fundamental level.

One of the most difficult challenges that the new cosmology will have to face is understanding the origin and nature of the cosmological constant. Ever since Einstein introduced it as a way to counteract gravitational attraction, it has haunted cosmologists and particle physicists. We still do not have a mechanism to explain its extraordinarily small value, 120 orders of magnitude below what is predicted by quantum physics. For several decades there has been the reasonable speculation that this fundamental problem may be related to the quantization of gravity. General relativity is a classical theory of space-time, and it has proved particularly difficult to construct a consistent quantum theory of gravity, since it involves fundamental issues like causality and the nature of space-time itself.

The value of the cosmological constant predicted by quantum physics is related to our lack of understanding of gravity at the microscopic level. However, its effect is dominant at the very largest scales of clusters or superclusters of galaxies, on truly macroscopic scales. We can speculate that perhaps general relativity is not the correct description of gravity on the very largest scales. In fact, it is only in the last few billion years that the observable universe has become large enough that these global effects could be noticeable. In its infancy, the universe was much smaller than it is now, and, presumably, general relativity gave a correct description of its evolution, as confirmed by the successes of the standard Big Bang theory. As it expanded, larger and larger regions were encompassed, and, therefore, deviations from general relativity would slowly become important. It may well be that the recent determination of a cosmological constant from observations of supernovae at high redshifts is hinting at a fundamental misunderstanding of gravity on the very large scales. If this were indeed the case, we should expect that the new generation of precise cosmological observations will not only affect our cosmological model of the universe but also a more fundamental description of nature.

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