PHILOSOPHY OF COSMOLOGY: WILL IT HELP US TO UNDERSTAND THE WORLD WE ARE LIVING IN?

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I have to warn the reader of this article that its author is neither a professional cosmologist nor astronomer but just a curious engineer amazed by the overwhelming advances made in the last; let's say 20 years, on our comprehension of the origin of the physical universe that we perceive around us. Such a progress is so impressive throwing at the same time light on ancient problems but also introducing deep and fascinating questions that belong up to the moment perhaps more to the realm of philosophy than to physical science. This state of affairs is not at all new in science and philosophy. Modern science, in particular quantum theory, although now a mature branch of physics is still fraught with interpretation issues that are perhaps now more profound than in the decades during which it was mainly developed. Perhaps for this reason the expression "*philosophy of quantum mechanics*" conveys today an accepted significance. Recently a group of professors from America's top philosophy departments, including Rutgers, Columbia, Yale, and NYU, set out to establish the philosophy of cosmology as a new field of study within the philosophy of physics[1]. The group aims to bring a philosophical approach to the basic questions at the heart of physics, including those concerning the nature, age and fate of the universe. A second group of scholars from Oxford and Cambridge launched a similar project in the United Kingdom[2]. As a result, more recently the expression "*philosophy of cosmology*" can be found in many academic papers and web sites[3].

There is no doubt that the first big question concerning the nature of the physical universe is: *Did the universe have a beginning or did it exist forever*? There are deep philosophical or metaphysical issues about this question. On the one hand, if the universe had a beginning, it was somehow created, but in this case: what accounted for that creation? As Stephen Hawking once said in a 1987 presentation[4], we return to the problem of the chicken and the egg. On the other hand, if the universe were eternal, what is eternity? A question that is not easy to respond and possibly this difficulty is related to the uncomfortable feeling infinitude brings to our minds. The problem is so inextricable for science that for centuries and up to the present

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[1] https://plato.stanford.edu/entries/cosmology/
[2] http://philosophy-of-cosmology.ox.ac.uk/
[3] https://www.closertotruth.com/tags/philosophy-cosmology
[4] Stephen Hawking "*The origin of the universe*", Three Hundred Years of Gravity Conference, Cambridge, June 1987.

the answer is many times found in religion recurring to the idea of God as the creator of the universe, or as its loving guardian in case the universe were eternal, God himself being an eternal, perfect and infinitely powerful entity beyond human comprehension.

In one or other form, Jewish, Christian and Islamic religions, recur to this type of "explanation" for the existence of the world. To avoid introducing an external agency for the creation of the world some Greek philosophers like Aristotle preferred to believe that the universe had existed and will exist forever.

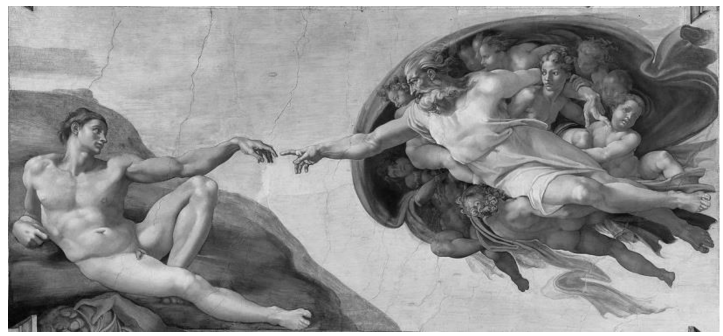

Fig. 1 – The creation of the world. Michelangelo c. 1508-1512. Sistine Chapel. Vatican.

For many years and up to rather recent times, science itself seemed defeated by this problem accepting that the origin of the universe was probably not assailable by the laws of physics as we know them. It is so that in the standard cosmological model widely accepted today by the scientific community, the evolution of the universe started after it was somehow created with very fine tuned properties that ensured its continuity to the present times and beyond. But this standard model said nothing on the mechanism of creation. A happy expression was coined by the British astronomer Fred Hoyle during a BBC radio broadcast on 28 March 1949, baptizing as "*big bang*" this mysterious and unknown creational process. Incidentally Fred Hoyle with other colleagues advocated for the so called "*Steady State Universe*" model in which new matter would be created as the galaxies moved away from each other. In this model, the universe is roughly the same at any point in time and so eternal.

But in the last two or three decades new theoretical and observational advances have been made that allow us to maintain some optimism about the possibility of answering some of the issues concerning the origin of the universe with hard scientific reasoning. It is usually accepted that modern cosmology started in the 20's with Hubble's observation that galaxies were on the average rushing away from each other. In his 1929 paper Hubble showed that the recessional velocity v of a galaxy cluster is proportional to its distance d from the Milky Way, that is $v = Hd$. The constant of proportionality H is known as the *Hubble constant* and remains as one of the most relevant parameters in cosmology since it gives the rate at which the universe is expanding, and this relationship indicates that the expansion is the same in all directions. The expansion of the universe is usually measured in term of a *cosmological scale* *factor* $a(t)$ function of time, defined in such a way that $d(t) = a(t)d_0$ where $d(t)$ is the physical distance between two points at time t and d_0 is the so called *comoving distance* between those point. The comoving distance is the distance between two points measured in any arbitrary scale that expands with the universe so that the comoving distance between any two points in space remains constant. It follows from the definition of the cosmological scale factor that

$$H(t) = \frac{da/dt}{a} = \frac{\dot{a}(t)}{a}$$

Until around 1920 the general belief among scientists was that the Universe was essentially static although not necessarily unchanging since from the XIX century increasing evidence of geological nature accumulated to suggest that the earth was in fact changing with time. This evidence led to conclude that the rocks and fossils present in the earth crust would require hundreds or thousands of million years to form and for this reason this process had to have necessarily a beginning. A more theoretical argument also suggested that the rest of the universe was also evolving and could not be eternal. One of the basic physical laws is the so called Second Law of Thermodynamics formulated by the German physicist Ludwig Boltzmann. This law, although of statistical nature, states that in any closed system the degree of disorder always increases with time[5]. Since the universe can be considered such a closed system, this implies that if the universe had existed for ever it would inevitably had reached a condition of complete disorder like a gas left to itself in a closed box and no change or temperature variation would be appreciable in such a system. This is in total contradiction to the evidence we observe in our universe where changes occur everywhere and temperatures can differ widely from one place to the other.

Now, this was the state of affairs as far as an unchanging universe is concerned. What about a static universe? Until around the late 20's the predominant idea was that although accepting the universe was not unchanging, it was essentially static. The idea of a static universe was appealing since Newton's time. However, Newton realized that the idea of a static universe introduced conceptual difficulties in front of Newton's own gravitation law. Since this law states that any two bodies will attract each other due to gravity, how would it be possible that a distribution of stellar objects avoid clumping together to a single point? The solution Newton found to this problem was that although a *finite* collection of stars could not remain motionless and end up falling together to a central point, accepting the universe was infinite, no central

[5] *Provided that dissipative phenomena take place that is the case in our universe.*

point could be identified and so there would be no possibility of clumping. Now we know that this reasoning is erroneous and the correct way to proceed is to start considering a finite distribution of stars and then to add more stars outside the region. Provided they are not initially moving with respect to each other, the final result is that the whole system will clump at some point. In the case the initial velocity of the stars is directed away from each other, the system might continue expanding but with the recession velocity slowing down by gravity. In neither case the system would remain static.

In the second half of the 1920 decade there had been already some theoretical evidence that after all the universe might not be static. In 1915 Einstein presented his General Theory of Relativity and his equations predicted that the universe should be expanding. However the ideas of a static universe were so ingrained in scientist's minds at that time that Einstein refused to accept this result and modified his equations introducing a term now designated *cosmological constant* that provided a repulsive effect that compensated the gravitational attraction and thus kept the universe static. In 1922 a Russian meteorologist by profession, Alexander Friedmann became interested in Einstein`s relativity theory and published a paper titled "*On the curvature of space*"[6] which described a universe that started from a point in space-time and ended in a great collapse. This models what is known today as a *closed* universe.

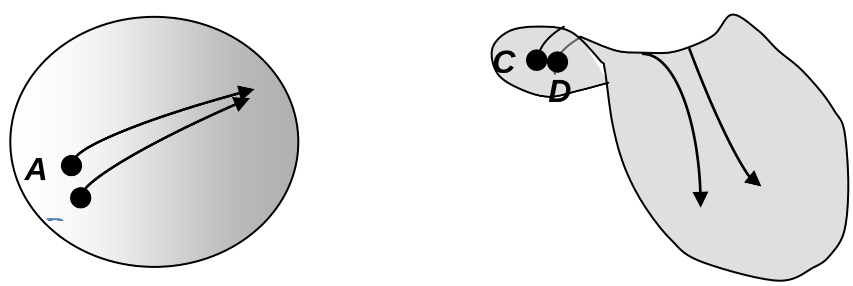

Fig. 2 - Paths on surfaces of different curvature.

The geometry of Universe is characterized by a parameter that represents its curvature. The three possibilities corresponding to this parameter are: "*Flat*" universe, "*open"* and "*closed"*. If the Universe is flat, that is, Euclidean, two particles that began a journey from some point in space with initially parallel directions would remain in parallel paths as long as they moved freely, that is, not subject to external forces. General relativity links the geometry of the Universe with its energy content. A flat Universe is such that its energy density is approximately 10^{-29} $g.cm^{-3}$ which constitutes a critical value. In a closed Universe the energy density has a higher value and in that case the trajectories of the two particles would tend to converge. Finally, a Universe with less than critical energy density would be open and particle trajectories would diverge.

[6] Alexander Friedmann "*Papers on curved space and cosmology*" MInkowski Institute Press, Jan.2014.

Fig. 2 schematically shows the last two cases. On the left we have the trajectories of the two particles that move on a closed two-dimensional surface such as that of a sphere and in which the initially parallel paths converge. We say in this case that it is a positive curvature surface. On the right we see the trajectories of the two particles on an open surface such as that constituted by the "*saddle*", on which the trajectories diverge, being in this case a surface of negative curvature.

Although our imagination does not allow us to visualize a curved three-dimensional space, let alone a four-dimensional space-time, we can understand the concept by analogy with a two-dimensional surface. Consider a plane, a sphere and a cylinder. Which of these surfaces is "*curved*"? Obviously, the plane is not. The sphere, on the other hand, is curved in an essential way, since it is impossible to deform it on a plane without being stretched or broken. The cylinder, on the other hand, can simply be unrolled on a plane without distortion or breakage. Therefore, we can consider it as a "*flat*" surface.

We can draw these conclusions easily because the surfaces considered are immersed in the three-dimensional space in which we find ourselves as observers. It was, however, one of Gauss's great achievements in the nineteenth century to demonstrate that the curvature of a surface can be determined intrinsically, that is, by measurements made locally on the surface by two-dimensional imaginary beings that inhabit it. Indeed, these beings could verify that on the surface on which they live the sum of the interior angles of a triangle constructed for example by means of tensioned ropes between three non-aligned points, it is always 180º and that the Pythagorean Theorem is fulfilled. In this way, without abandoning their two-dimensional world, these beings can verify that the geometry of that world is Euclidean. With the perspective that gives us to inhabit a three-dimensional world, we know that in this case the two-dimensional surface can be a plane or a cylinder, since in local measurements, the difference is non-existent. On the other hand, if the beings existed on the surface of a sphere, they would verify that the sum of the interior angles of a triangle is always greater than 180º and that the Pythagorean theorem is not fulfilled. The conclusion would then be that the geometry of the two-dimensional world they inhabit is not Euclidean.

I can be shown that the critical energy density of the universe that makes it flat is

$$\rho_{Crít} = \frac{3H_0^{\ 2}}{8\pi G}$$

where G is the universal constant of gravitation and H_0 is the present value of the Hubble parameter in which we reserve the subscript "$_0$" to denote current values of the variables considered. The energy density of the universe $\rho(t)$ is the energy per unit volume. This energy can be expressed either in units of mass or in units of energy since both energy and mass are related by the Einstein's well-known formula $E = mc^2$, E being the energy, m the mass and c the speed of light in vacuum. So when we refer to total average energy density in the universe, we include all sorts of masses and energies.

More generally the evolution of the scale factor is given by the *Friedman equation*

$$H^2(t) = \frac{8\pi G}{3}\left[\rho(t) + \frac{\rho_{Crít} - \rho_0}{a^2(t)}\right]$$

in which $\rho(t)$ is the average energy density of the Universe as a function of time and ρ_0 the current value.

To understand the history of the Universe we must analyze the evolution of the scale factor a with the cosmic time t. General relativity also provides us here the relationship between this evolution and the energy of the Universe. **Fig. 3** shows how the scale factor increases with the evolution of the Universe.

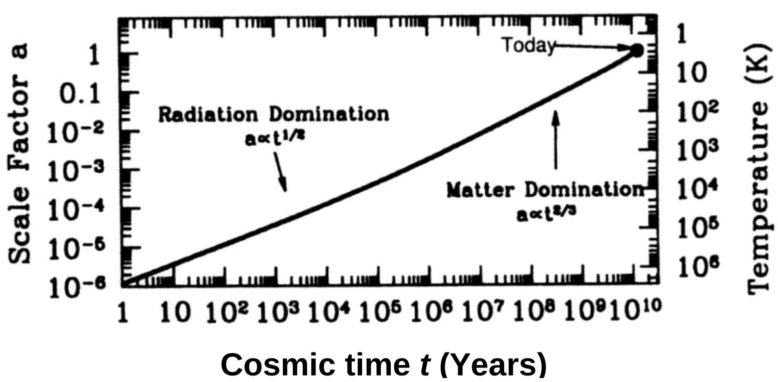

Fig. 3 – Evolution of the scale factor of the universe as a function of cosmic time.

In past times, factor *a* varied with time proportionally to $t^{1/2}$ to do so later proportionally to $t^{2/3}$. As we will see, the way in which the scale factor *a* changes over time is determined by the energy density of the Universe. In early times, radiation was the dominant form of energy, while in later times most of the energy was represented by the non-relativistic (i.e. rest) mass of the particles present. In fact, one of the ways to evaluate the energy content of the Universe is by measuring changes in the scale factor. We will see that as a result of this analysis, there are indications that very recently factor *a* has stopped increasing proportionally to $t^{2/3}$, which would imply that it would begin to dominate a new form of energy in the Universe.

If the Universe is flat and dominated by matter, it is $a \propto t^{2/3}$, so it gives $\mathrm{d}a/\mathrm{d}t \propto (2/3)t^{-1/3}$ and therefore $H = (2/3)t^{-1}$. So an effective way to verify the cosmology of the Universe is to independently measure the rate of change of Hubble parameter H_0 and the age t_0 of the Universe. It arises immediately from the above that in a flat universe dominated by matter, the $H_0 t_0$ product must be equal to 2/3.

Since for a flat Universe it is $H_0 t_0 = 2/3$, the expected age for such a universe would be $t_0 = (2/3)/H_0 \cong 8$-10 Gyr, the best current estimate being between 13 and 14 Gyr which suggests that the idea of a flat universe dominated solely by matter would not be viable. In recent years there have been observations that suggest that there may be in the Universe another form of energy other than radiation and ordinary matter. This form of energy is known as *dark energy* and one possibility is that it represents a constant value of energy density.

This additional energy contribution of the Universe is introduced through the so-called *cosmological constant* Λ. The history of this cosmological constant is curious. Einstein introduced it into his field equations in 1917 as an antigravity effect to achieve a static universe, however, when Hubble in 1929 states that galaxies move away from the local group to which our milky way belongs and that therefore the universe It is expanding, Einstein eliminates it from its equations and practically until the beginning of the '90s, cosmologists assumed its value was nil. However, from those years, new observational evidence led to reconsider it.

The cosmic microwave radiation background.

We must refer now to the *cosmic microwave radiation background* (CMB). This radiation background consists of an isotropic flow of radiation that comes from space in all directions and was first detected by radio astronomers Arno A. Penzias and Robert W. Wilson in 1964 while working with a radio antenna in a laboratory of Bell Telephone in New Jersey, USA. This radiation background offers us a vision of the Universe when it was only about 300,000 years old. The photons that make up the CMB began to travel as free radiation when the temperature of the Universe dropped to about 3000 ºK when the density of electrons present became low enough for the coupling between electrons and photons, that is, the dispersion of the photons by electrons, became negligible. From that moment on, the Universe became transparent to the photons that have continued to travel freely until today.

It is interesting that in 1965, a young theoretical physicist from Princeton, P.J.E. Peebles, published a work in which he speculated about the possibility that there could be a microwave background from the early Universe with an equivalent current temperature of approximately 10ºK. Peebles' work was inspired by the ideas of Robert H. Dicke, a leading Princeton experimental physicist who in 1964 already wondered if there could be no observable radiation remaining from a warmer and denser stage of the Universe. Previously, some theoretical speculations had already been made, among which the work carried out in the 1940s-50s by George Gamow and his collaborators Ralph Alpher and Robert Herman, who had developed a theory of nuclear synthesis based on the idea of a primeval "great explosion ". In 1948 Alpher and Herman made from this idea the prediction of the existence of a cosmic radiation background with a temperature of 5ºK. Similar calculations were made in 1964 by Y.B. Zeldovich in Russia and independently by Fred Hoyle and R.J. Tayler in England.

The measurements made by Penzias and Wilson were made at the wavelength of 7.35 cm and the equivalent temperature was set at 13.5ºK. Under the hypothesis that the early Universe was much hotter and denser than at present, it can reasonably be considered that under such conditions the rapidity of interaction between particles, that is between photons and mainly electrons, was much higher than the rate of expansion and the state of the Universe evolved from a thermodynamic quasi-equilibrium to another. Now, the distribution of radiant energy of a black body in thermal equilibrium is given by Planck's formula

$$\rho_T(\lambda)d\lambda = \frac{8\pi hc}{\lambda^5}\frac{d\lambda}{e^{hc/\lambda kT}-1}$$

where $\rho(\lambda)d\lambda$ is the black body radiation energy per unit volume within the wavelength range λ to $\lambda + d\lambda$. T is the absolute temperature, k the Boltzmann constant (k = 13.38 x 10^{-16} erg/ºK), c the speed of light in a vacuum and h the Planck constant (h = 6.665 x 10^{-27} erg.s).

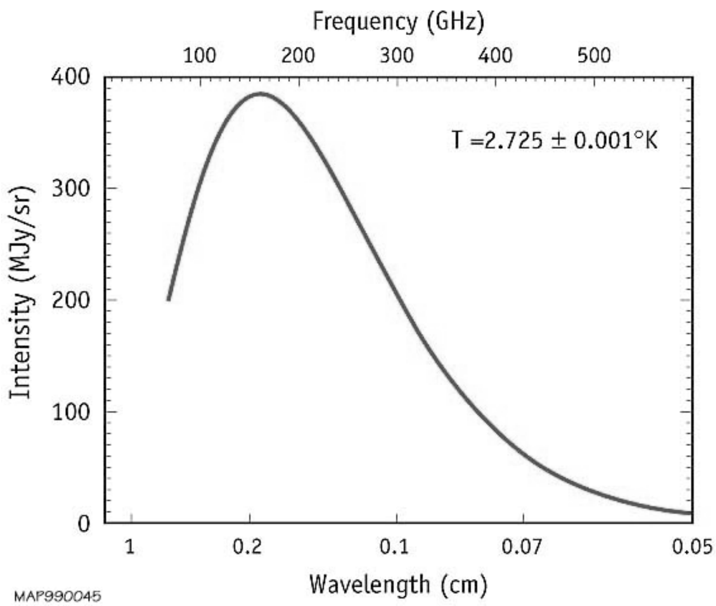

Fig. 4 – Cosmic microwave radiation spectrum measured by FIRAS spectrophotometer on board the COBE satellite. The curve represents dozens of measurements with a margin of error less than the thickness of the line.
(1 Jy (Jansky) = 10^{-26} W.m^{-2}.Hz^{-1} = 10^{-23} erg.s^{-13}cm^{-2}.HZ^{-1})

Fig. 4, shows the total correspondence between the measured energy intensity values and those that represent the radiation of a black body at a temperature of 2.7 ºK. During expansion the black body radiation continues to obey Plank's law but with temperature that decreases in proportion to the scale of expansion.

The "big-bang"

The thesis on which all the cosmology of the "*Big Bang*" rests is that approximately between thirteen and fourteen billion years ago, any two points of the observable universe were arbitrarily close. This means that at that moment, the light had not yet had time to travel more than an infinitesimal distance and therefore the horizon for any observer (if it could have existed in such circumstances), was infinitely close. All this implies that the universe constituted what we call a singularity, that is, it was limited to a point where the density of matter-energy became infinitely high.

The two questions that arise immediately around this hypothesis are: How old is our Universe that evolved until today from that singularity? And did the Universe exist before it? Cosmology can answer the first question with reasonable certainty; the second does not have an answer, at least so far, in the field of science. We can imperfectly visualize the big bang as a kind of explosion from that singularity that gave rise to the expansion of the Universe and the recession movement of galaxy systems according to Hubble's law.

The most precise estimates of the Hubble H_0 constant at the time of writing these lines yield a value for this of (67.5 ± 1.2) km/s /MPc, with a MPc (Megaparsec) approximately equal to 3 million light years. The resulting age of the universe would be 113.8 billion years (13800 million years).

Since the Hubble constant is so small, the recession velocity of the galaxies close to ours is consequently small and its general recession movement is then masked by the local movements that these nearby galaxies, belonging to the so-called *Local Group*, can exhibit. This Local Group is a galaxy system in which the Milky Way along with Andromeda are the dominant ones as well as other accompanying galaxies. As these galaxies orbit one in relation to the others, they do not show clearly to take part in the expansion movement of the farthest galaxies.

We have seen above that if the Universe has the average critical density

$$\rho_{Crít} = \frac{3H^2}{8\pi G}$$

it would be a marginally open flat universe, that is to say in which galaxies would have the energy barely necessary to move away infinitely.

Remember that this critical density corresponds to a value

$$\begin{aligned}\rho_{Crít} &= 1.88h^2 x 10^{-29} \text{ g cm}^{-3} = \\ &= 1.88x0.72^2 x10^{-29} \text{g cm}^{-3} \approx \\ &\approx 10^{-29} \text{g cm}^{-3}\end{aligned}$$

This is certainly a value that represents very little matter, a few hydrogen atoms per m^3. In cosmology it is usual to define the radius between the average density of the universe and the critical density, identifying it with the letter Ω. That is to say

$$\Omega = \frac{\rho}{\rho_{Crít.}}$$

so that if Ω = 1, we have a flat universe, of zero curvature but marginally open, if Ω> 1, the Universe would be spherical, of positive curvature and closed, that is, the galaxies could not move away indefinitely and the expansion would stop and eventually his movement would be reversed leading to what is known as the "*Big Crunch*". Finally, if Ω <1, we would have a hyperbolic Universe, of negative curvature and open in which galaxies could expand indefinitely. Both in the latter case and with the flat Universe, the Universe would continue to expand until the "*thermal death*", a situation that has been called the "*Big Chill*", although in the latter case it would do so more slowly than in the first.

In general, the preference of cosmologists turns to accept a value of Ω = 1, among other reasons because this value is the only one consistent with an inflationary universe scenario, which we will refer to.

However, if the number of galaxies is counted in a sufficiently large volume, say of the order of one billion light years, we multiply this number by the average total mass of stars in each galaxy, and divide this value by the volume considered, we would obtain the average density of visible matter in that volume. The problem that arises is that the value resulting from such an estimate is approximately 0.5% of the critical density, that is to say Ω = 0.005. While it is true that there may be significant errors in these calculations, these would not imply variations greater than 100%. So, at most visible matter can contribute 1% to critical density. Where does the other 99% come from, if the Universe really has critical density?

A part of the missing mass may be given by non-luminous matter, and therefore not visible, in and around the galaxies. Clouds of gas and dust, dark stars and eventually even black holes, which could account for three times the visible mass, which would be consistent with the observed movements of galaxies. Anyway, we would still be with Ω = 0.1, still very short of the critical density!

So to reach that critical density value, it would require that not only most of the matter in the Universe is not luminous but that there should be some new and strange type of matter very different from the familiar electrons, protons and neutrons that constitute everything that surrounds us. In addition, this hypothetical and mysterious "*dark matter*" should not be located in the large aggregates of visible matter since otherwise it would have been detected by its gravitational influence on the movement of galaxies. What this dark matter consists of and how it is distributed in the Universe is one of the biggest questions of today's cosmology.

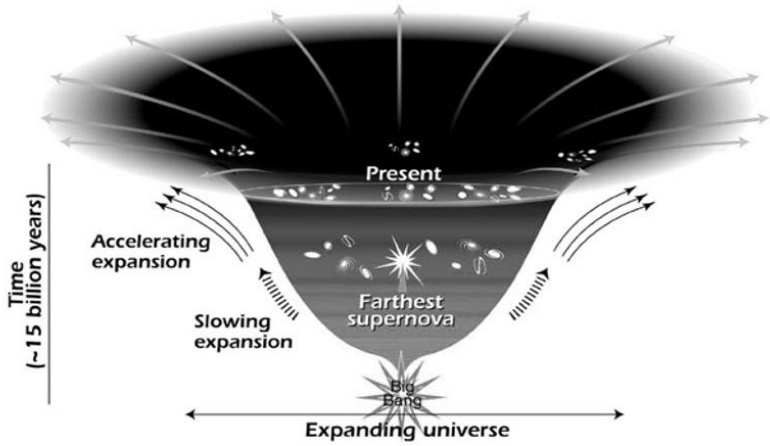

Fig. 5 – Schematic description of the acceleration of the expansion of the Universe that began about 7.5 billion years ago..

Thus, until the beginning of the 1990s, what was considered true is that the density of the Universe could be so low that it did not exceed the critical value and the expansion continued forever or that the density was so high as to stop that expansion. In any case, the expansion rate should be reduced over time by the effect of gravitational "*braking*". However, in 1998 the Hubble Space Telescope (HST) observations made on very distant supernovae showed evidence that the Universe expanded in the past more slowly than at present. So, the expansion of the Universe, against everything thought until then, is accelerating instead of slowing down. Cosmologists certainly do not yet have an answer to this effect, but at least they have given it a name: "*dark energy*".

What is the nature of this dark energy remains a mystery until the moment of writing this. What can be estimated is its quantity due to its effect on the speed of expansion of the Universe. It is estimated that dark energy represents 68% of the total energy of the Universe, dark matter would contribute around 27%, and the rest, less than 5%, would be the contribution of "ordinary" matter. **Fig. 5** schematically shows this acceleration that begins approximately at the average age of the Universe, that is to say about 7.5 billion years ago. As usual in space-time representations, the three-dimensional physical space is displayed on the horizontal scale in a single dimension while time corresponds to the vertical scale.

An explanation for dark energy is that it is a property of space. This interpretation arises from the introduction by Einstein of the cosmological constant to which we have already referred to earlier. According to this interpretation, empty space has its own energy and since it is an intrinsic property of space, it is not diluted as space increases with the expansion of the Universe. As a result, this form of energy would cause an increase in the speed of expansion. Unfortunately, so far no one knows why the cosmological constant intervenes in the field equations of relativity or why it has the value produced by the observed acceleration of the expansion of the Universe.

Another alternative explanation of why space has energy comes from quantum field theory. In relation to this, it is accepted that the empty space is the seat of virtual processes of creation and annihilation of particles made possible by the Principle. of Uncertainty, but the calculations made so far by physicists suggest that the energy that space acquires by these virtual processes exceeds by a factor of 10^{120}, nothing less!, the one required to explain the acceleration of expansion so the mystery continues .

Another explanation, which does not explain yet anything, is the hypothetical presence of a new type of force field that fills the entire space and has an effect contrary to gravitation. The physicists who postulated it have named it "*quintessence*" in reference to the 5^{th} element of the Greek philosophers.

Of course, one last possibility, but that scientists are not willing to accept lightly, is that Einstein's general theory of gravitation is incorrect. This would require a new theory that, in addition to the acceleration of the expansion of the Universe, allows us to understand its structure and evolution.

Based on theoretical models and observations, cosmologists have concluded that the total energy content of the Universe is as indicated above, that is ~68% dark energy, ~27% dark matter and ~5% “normal” matter. With respect to the second component, that is to say the dark matter, it is almost certain that it is not barionic matter (protons and neutrons) for example in the form of clouds because it would be detected by the absorption of the radiation that passed through them. It is also not antimatter, because the gamma radiation that would occur when annihilated with ordinary matter is not observed. Finally, it is not likely to constitute giant black holes of galactic dimensions because a gravitational lens effect corresponding to such objects is not observed. The most favored hypotheses at the moment are on the one hand that dark matter is constituted by exotic particles such as WIMPS (Weak

Interacting Massive Particles). These would be particles that possessing mass, interact very weakly so that they can pass without difficulties through matter Candidates for these particles would be neutrinos, axions and neutralins. Nevertheless neutrinos, if they have mass, it is anyway too small to make a significant contribution to dark matter. Axions are particles that have been proposed to explain the absence of an electric dipole moment in the neutron and although they would not possess much mass, they could have been produced in abundance in the big bang. They have not been detected until the moment of writing this. Neutralins on the other hand, would be massive particles, 30 to 5000 times the mass of the proton, but its search still continues.

The other hypothesis regarding dark matter is that it is "*Massive Compact Halo Objetcs*" (MACHOs), which would be compact objects of ordinary matter with sizes that could range from that of a small star to that of super-massive black holes.

The problems with the conventional big bang theory.

The first problem that is not possible to solve within the big bang theory framework is the so called *Homogeneity* or *Horizon problem*. The big bang model, as we shall see, is unable to explain the uniformity of the Cosmic Microwave Background Radiation (CMB) at the time of decoupling when the universe was about 370000 years old. Measurements today show that this uniformity amounts to 1 part in 10^5, certainly an amazing uniformity.

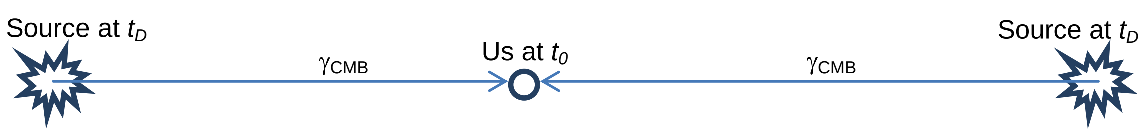

Fig. 6 – Cosmic microwave background radiation arriving us from opposing locations of the universe.

We know that the temperature of the universe at the time of decoupling t_D was around 3000 K which is about the temperature at which hydrogen atoms can be formed and the hot plasma became transparent enough so that the photons were able to escape from it. From this we can calculate the physical distance $l_P(t_0)$ from the source to us today, which is

$$l_P(t_0) \approx 28.2 \times 10^9 \text{ light years}$$

On the other hand, the *horizon* at that time $l_{hP}(t_D)$, that is the maximum distance light could have traveled from the time of decoupling, was

$$l_{hP}(t_D) \approx 1.1 \text{ x } 10^6 \text{ ligth years}$$

that is significantly less than $l_P(t_D)$. So $l_P(t_D)/l_{hP}(t_D) \cong 23$ which means that at the moment of decoupling the sources in **Fig. 6** were about 46 horizon distances apart from each other making impossible for the sources to have any causal connection between them. It is possible to assume that the singularity from which the universe evolved was perfectly uniform and homogeneous, but this is an assumption and not and explanation. To *explain* the uniformity of temperature at the big bang some other reasoning is needed. As we shall see inflation provides this explanation.

What we are going to consider now is how close to 1 at t = 1s must have Ω been for Ω to be in the range we know it is today. The time of 1s is selected as appropriate because all the evidence suggests that the big bang model describes correctly the evolution of the universe from that instant to the present. Calculations lead to an estimate $|\Omega - 1|_{t=1\text{second}} \leq 10^{-18}$ which means that when the universe was 1 second old Ω = 1 to an accuracy of 18 decimal places! But the problem arises that there is no reason a priori whatsoever for Ω to have that particular value. We can circumvent the problem just accepting as a postulate that the universe at the big bang started with a value for Ω equal to or extraordinary close to 1, but this is not an explanation. Again, we shall see how inflationary cosmology solves this riddle.

A third problem that arises within conventional big bang cosmology is the so called *Magnetic Monopole problem*. According to the original Big Bang theory, there should be a vast number of heavy, stable "*monopoles*", or a magnetic particle with only a single pole. Grand Unified Theories propose that at high temperatures (such as in the early universe) the electromagnetic force, strong, and weak nuclear forces are not actually fundamental forces but arise due to spontaneous symmetry breaking from a single gauge theory. These theories predict a number of heavy, stable particles that have not been observed in nature. The most notorious is the magnetic monopole, a kind of stable, heavy "charge" of magnetic field. Monopoles are predicted to be copiously produced following Grand Unified Theories at high temperature and they should have persisted to the present day, to such an extent that they would become the primary constituent of the Universe. Not only that is not the case, but all searches for them have failed, placing stringent limits on the density of relic magnetic monopoles in the Universe. Inflation diluted the number of monopoles in the Universe so we don't detect them today. A period of inflation that occurs below the temperature where magnetic monopoles can be produced would offer a possible resolution of this problem: monopoles would be separated from each other as the Universe around them expands, potentially lowering their observed density by many orders of magnitude.

Why inflation?

It is common saying among scientists that the standard cosmological "*big bang*" theory leaves the "*bang*" wanting. This is true to some extent since this theory says nothing about the causes that gave rise to our universe. Instead, it takes for granted that the universe is created out of nothing and from that event onwards space and time appear and the universe evolves expanding up to the present time. So, the big bang theory is really a model that pretends to describe the evolution of the universe from the instant *after* it was created up to the present.

The inflationary hypothesis is a modification of the standard cosmological big bang theory that comes to the rescue of this and other problems that the standard model leaves unanswered. These problems are: *the horizon problem*, *the flatness problem* and the *monopole problem*, among others as we shall see.

The inflationary hypothesis was proposed by the American physicist Alan Guth in 1979 while he was working as a postdoctoral fellow at the Stanford Linear Accelerator Center. What this hypothesis basically states is that the space in the very early universe underwent a tremendous but very brief burst of expansion. This burst of inflation lasted only from 10^{-35} to some moment between 10^{-33} and 10^{-32} seconds after the singularity out of which the universe supposedly appeared. Then the expansion of the universe continued but at a much slower pace. So the idea is that once the space and time (or should we better say *space-time*?) were created at the singularity, space-time experienced a gargantuan burst of expansion which led the initial point singularity to an expansion factor of more than 10^{30}, perhaps 10^{100} in an incredible brief process lasting only for about 10^{-35} seconds. This increase in size of the universe was so large and so fast that far exceeded all the expansion the universe experimented in the 14 billion years since the end of the inflationary phase to the present. It is important to take into account that although de expansion rate during inflation was much higher than the velocity of light in vacuum, this does not contradict relativity theory since it was space itself that was expanding. According to this, the light and radiation emitted by the vast majority of the universe could not have yet reached us and some shall not arrive before the sun and the earth extinguish. This is the reason why our observable region of the universe is but a speck of dust in the immensity of the entire cosmos.

So the story goes like this: once the universe was created, or to be more careful with the wording, once the universe began its existence as a chaotic hot soup of particles and radiation and *after* a brief interval of about 10^{-36} seconds, a tremendous burst of expansion took place. This burst of expansion lasted for only about 10^{-35} seconds but as we shall see had enormous consequences in the succeeding evolution of our universe, among these its smoothness, flatness and large-scale isotropy.

Let's analyze first which is the mechanism today with the largest acceptance within the physicist's community that explains the origin of this gigantic outward push the universe experimented during the inflation period. There are so far four basic forces recognized that govern the behavior of our physical world. These are: the electromagnetic force, the nuclear weak force, the nuclear strong force and gravitation. Quantum Field Theory (QFT) teaches us that all these forces arise from the existence of their corresponding fields. Although presently these fields appear as independent one from the other in the early universe, even before the onset of the inflationary stage, when the universe was about 10^{-36} seconds old, the temperature was sufficiently high to make the first three fields indistinguishable and unified in a single force field.

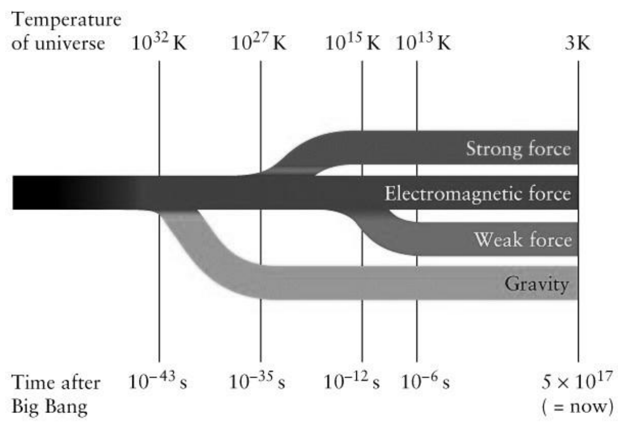

Fig. 7- Unification of force fields at different stages of the universe evolution.

As universe expansion progressed and average temperature decreased, this unification started to decay and each force field began to acquire its present identity. **Fig. 7** shows schematically the sequence of this process as a function of the temperature of the universe and its corresponding age according to QFT. We must note that the unification of gravity with the other forces is still to some extent speculative.

Now, to explain the burst of inflation another force field must be brought to the stage. Although there is so far no direct observable evidence of its existence, physicists in general accept its reality and baptized it *inflaton field*. This still speculative inflaton scalar field permeates the whole universe. The scalar field potential energy as a function of the field value is shown in **Fig. 8**. The inflaton field may be identical to vacuum energy reason for which the configuration of the inflaton field at the higher potential values is referred to as *false vacuum* and the configuration at the global minimum as *true vacuum*. In a strictly classical analysis the field could remain indefinitely at the maximum value nevertheless that the slightest perturbation would send the potential rolling downhill towards the global minimum shown in the figure. In the quantum realm the Uncertainty Principle forbids a fixed value for the scalar field so there will be inevitable quantum jitters that sooner or later will send the field potential rolling downhill. The resultant reduction in potential energy will be converted into gravitational *repulsive* energy and this repulsive gravitational energy will drive the inflationary process.

We have seen that the inflationary period lasts only about 10^{-35} seconds. This is consistent with the structure of our universe. Had the inflation lasted a bit more or a bit less than this value, we would not have now the universe we observe. So the shape of the curve of **Fig. 8** has to be adequately tuned in order to have a period of inflation adjusted to the required value. The different curves that have been proposed so far with this goal are variations of the one shown in the figure and differ only in details.

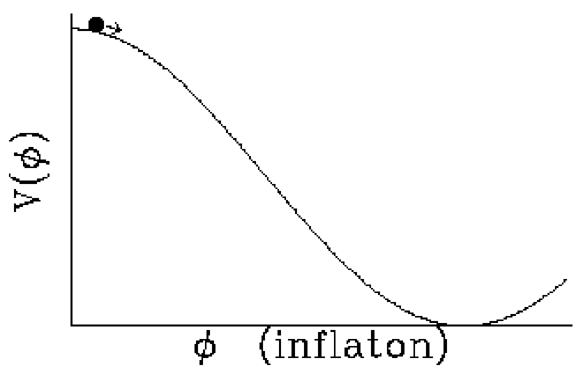

Fig. 8 – Potential vs. inflaton value

To understand the magnitude of the repulsive effect of negative gravity we have to take into account that the value of the inflation field is at each moment constant throughout the space and that although it will vary at each instant, during the inflationary period this variation will be small. Only when the potential has rolled downhill significantly the potential shall be reduced to a value sufficient to halt the inflationary process. The idea of negative gravity is not new. Einstein made use of it when he introduced the cosmological constant in his equations of general relativity. He did so because his original equations inexorably led to a non-static universe, an idea that he rejected. So, he tuned the value of the cosmological constant in such a way that it balanced exactly the inward pull of gravity. When the astronomical observations of Hubble showed that the universe was far from static but on the contrary it expanded, Einstein with some embarrassment erased the cosmological constant from his equations. Nowadays, the idea of a cosmological constant has been revived but under a somewhat different view. According to this view, the cosmological constant and its negative gravity effect would be the result of the presence of an energy field permeating the universe. The scientists have baptized this energy field "*dark energy*". This dark energy field would be no other than the inflation field and according to calculations made by Guth and Tye, the energy of the inflation field amounts to 10^{100} times de energy of the original Einstein's cosmological constant.

Now for the solution of the riddles. The solution of the Friedmann equation for a flat space lead to

$$a(t) = \text{Const.}e^{\chi t}\text{; } \chi = \sqrt{\frac{8\pi G}{3}\rho_F}$$

which implies exponential expansion during false vacuum energy density domination.

Some sample numbers obtained from experimental observations at accessible energy scales and extrapolated theoretically according to GUT theory[7] suggest that the energy scale of GUT interactions is of the order $E_{GUT} \cong 10^{16}$ GeV and the false vacuum energy density $\rho_F \cong 2.3 \text{ x } 10^{81}$ g.cm^{-3} an incredibly large number. $\chi^{-1} \cong 2.8 \text{ x } 10^{-38}$ s and $c\chi^{-1} \cong 8 \text{ x } 10^{-28}$ cm which is about 15 orders of magnitude smaller than a proton. Let's assume now that we have a small "patch" of this size at the beginning of inflation then at the end of inflation that is about 10^{-35} s later the patch shall have grown to a size about 1to10 cm or more. Bearing in mind that the product aT remains approximately constant, it is possible to write in terms of energy an estimate of the present size of the universe assuming it started with a "patch" of about this size at the end of inflation and continued to grow at a slower pace as predicted in the conventional big bang picture

$$\frac{a(t_0)}{a(t_{\text{End of inflation}})} \text{x 10 cm} = \frac{10\,\text{GeV}}{k_B 2.7\text{K}} \text{x 10 cm} =$$
$$= 450 \text{ x } 10^9 \text{ ligth years}$$

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[7] GUT: Grand Unified Theory is a model in particle physics in which, at very high energies in the past, the three gauge interactions of the Standard Model, the electromagnetic, weak, and strong interactions, or forces, are merged into a single force. Although this unified force has not been directly observed, the GUT models theorize its existence. If unification of these three interactions is possible, it raises the possibility that there was a grand unification epoch in the very early universe in which these three fundamental interactions were not yet distinct.

This figure is way off the present estimated value for the age of the universe suggesting that possibly the final size of the "patch" after inflation might have been less than 10 cm, maybe 1 cm or so.

The previous figures lead to a simple explanation of the Horizon-homogeneity problem. If the universe started with a tiny "patch" of the order of event horizon that is about 8 x 10^{-28} cm in size so thermal equilibrium would prevail and once inflation takes over this "patch" shall grow to about 1-10 cm in size with a uniform temperature that is inherited by our present universe.

The Flatness problem is also immediately explained by inflation since during the inflation process the universe is vacuum energy density ρ_F dominated and the Friedmann equation results

$$H^2 = \frac{8\pi}{3} G\rho_F - \frac{kc^2}{a^2}$$

Since ρ_F remained essentially constant during inflation, the first term of the right hand side of this last equation remained constant and since $a(t)$ increased during inflation by a factor 10^{28} the second term was reduced by a factor of 10^{56} which made this term negligible and resulted in a flat universe.

The Monopole problem is also solved considering the fantastic expansion of 10^{28} in size of the initial "patch" which represents 10^{84} increase in volume. So assuming the monopoles were formed *before* inflation started, their number per unit volume would be so reduced after inflation that justifies why they have not been detected until now.

One more consideration is in order. The visible part of the universe contains about 10^{90} particles. In standard cosmological models these particles were there from the start. Any theory that pretends to describe the origin of the universe must somehow explain how this tremendous amount of particles came into being. According to Alan Guth[8] the easiest way to get this number is a calculation involving an exponential. The exponential expansion of

[8] Alan H. Guth "*Eternal inflation and its implications*". 2nd International Conference on Quantum Theories and Renormalization Group in Gravity and Cosmology (IRGAC 2006), Barcelona, Spain, July 2006,

inflation reduces the problem of explaining 10^{90} particles to the problem of explaining 60 or 70 *e*-foldings[9] of inflation. Since within the framework of inflation it is not difficult to produce models implying far more than 70 *e*-foldings this suggests that the observed universe may be just a speck in the entire universe.

Universe or multi-verse: a physical or metaphysical problem?

Until around 1960 cosmology was widely regarded as a branch of philosophy. Nevertheless, it has evolved to an extremely active area of physics and astronomy. However, there were two main issues that made the philosophy of cosmology unlike that of any other science. The first is, "*The uniqueness of the Universe: there exists only one universe, so there is nothing else similar to compare it with*" The second is "*Cosmology deals with the physical situation that is the context in the large for human existence: the universe has such a nature that our life is possible*".

We have seen that our visible universe evolved from a nugget sized "patch" of about 1 cm across to the present size of about ninety-three billion light years. The idea that the universe arose from a single "bubble" during the GUT phase transition of spontaneous symmetry breaking has tremendous implications. Each horizon volume that existed before inflation could have evolved in its very own independent universe. This opens the possibility that many other "patches" or bubbles might have existed that could have led to the creation of a multitude of other "parallel" universes, universes about which we have no possibility whatsoever of knowing neither in the present nor in the future unless some very unlikely event like bubble collision happens. So the first statement above concerning the uniqueness of our universe is now put seriously in doubt.

This begs several questions. The first one being: is our universe unique or just a member of a possibly infinite array of universes? And what is the stuff that existed between bubbles at the moment of inflation. Was it a realm of undifferentiated symmetric space where all forces are unified? How did it evolve? Is it a realm where all particles are identical and matter as we know it does not exist and where vacuum energy is the sole component? Many cosmologists have argued in favor of a specific version of the multiverse called *eternal inflation* (EI) as proposed by Alexander Vilenkin[10] and Paul Steinhardt[11] in 1983. Although false vacuum is a

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[9] *e*-folding is the time interval in which an exponentially growing quantity increases by a factor of *e*; it is the base-*e* analog of doubling time.
[10] Vilenkin, A 1983 "*The birth of inflationary universes*" Phys. Rev. D 27, 2848–55.

metastable state, decay of the false vacuum, which is the rolling downhill of its potential, is an exponential process very similar to the decay of a radioactive substance. The probability of finding the inflation field at the top of the plateau in its potential energy diagram diminishes exponentially with time. One important difference with de decay of a radioactive substance is that the false vacuum expands at the same time that it decays. Actually, for the inflationary model to work the inflation field must expand much faster than it decays. Then, although the false vacuum is decaying, it does not disappear, and the total volume of the false vacuum continues to grow exponentially with time in a never-ending expansion.

According to this, the rapid expansion predicted by inflationary cosmology continues in some regions and comes to an end (with a transition to slower expansion) in others. This leads to a global structure of "pocket" universes embedded within a larger multiverse. This process will repeat itself literally forever, producing a kind of a fractal structure to the universe, resulting in an infinite number of local universes. This is quite distinct from the multiverse of superstring theory, where it is supposed, by Susskind among others, that every vacuum state is realized, or from the multiverse of the many-worlds theory of quantum mechanics as proposed by Everett. All these ideas are highly hypothetical and controversial and for these reasons are better installed in metaphysics than in current physical research. Nevertheless, we must not forget that many ideas that belonged to the realm of metaphysics at one time evolved to become hard physical facts. For example, detection of a distinctive signature resulting from bubble universe collisions that cannot be explained by other means would provide evidence for the multiverse. However, there is no expectation that a multiverse theory would generically predict such traces; for example, if the collision occurs too early the imprint may be erased by subsequent inflationary expansion. One question that remains unanswered is the origin of the very low vacuum energy density of our universe. We have already seen that vacuum energy is what hypothetically drives inflation; however, no theoretical model to account for the low value of the required present vacuum energy density is available. All calculations result in values way off the observed value by a huge order of magnitude. One aspect related to this to which we have already referred but is worth recalling is that vacuum energy density remains constant as the universe expands. This might seem at first glance a violation of the principle of conservation of energy. However, and fortunately for the conservation of energy principle this is not so since the increase in vacuum energy during inflation is exactly compensated by the

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[11] Steinhardt, P J 1983 *"Natural inflation, in The Very Early Universe"*, Proceedings of the Nuffield Workshop, Cambridge, 21 June – 9 July, 1982, Eds: Gibbons, G W, Hawking, S W and Siklos, S T C (Cambridge: Cambridge University Press), pp. 251–66.

negative gravitational potential energy that also rises during expansion. So, it well may be that the energy of the initial bubble does not need to be large to start inflation, actually it can be close to zero. Inflation shall feed from gravitational energy to survive.

The philosophical, not to say religious, implications of the multiverse model are so profound that boggle the mind. There is no question that this issue ranks among the most attractive areas of present physical and metaphysical research.

Other so far physical/metaphysical issues.

Discovery of new fundamental physics such as exotic dark energy and dark matter, or a small universe curvature to name a few possibilities of what may be awaiting us at the turn of the corner. The visible universe including Earth, the sun, other stars, and galaxies is made of protons, neutrons, and electrons bundled together into atoms. Perhaps one of the most surprising discoveries of the 20th century was that this ordinary, or baryonic matter, makes up less than 5 percent of the mass of the universe. Dark matter produces an attractive force (gravity), while dark energy produces a repulsive force (antigravity). Together, they make up 96 percent of the universe and we can't see either. Astronomers know dark matter exists because visible matter doesn't have enough gravitational muster to hold galaxies together. Scientists have not yet observed dark matter directly. It doesn't interact with baryonic matter and it's completely invisible to light and other forms of electromagnetic radiation, making dark matter impossible to detect with current instruments. But scientists are confident it exists because of the gravitational effects it appears to have on galaxies and galaxy clusters. However, scientists still don't know for sure what they really are. We have considered some possibilities, but the solution is still controversial.

A rather different approach to the evolution of the universe that does not require a beginning and can dispense with the idea of a multiverse is the idea of cyclic universe. Recently Ana Lijas and Paul Steinhardt[12] wrote a paper in which combining intervals of ultra-slow contraction of the universe with a non-singular classical bounce naturally leads to a novel cyclic theory of the universe in which the Hubble parameter, energy density and temperature oscillate periodically, but the scale factor grows by an exponential factor from one cycle to the next. According to the authors the resulting cosmology not only resolves the homogeneity, isotropy, flatness and monopole problems and generates a nearly scale invariant spectrum of density

[12] A. Lijas; P. Steinhardt "*A new kind of cyclic universe*" Preprint submitted to Elsevier, April, 2019.

perturbations, but it also addresses a number of age-old cosmological issues that big bang inflationary cosmology does not.

To make things even more arguable, it is worth mentioning that a prestigious British mathematician and physicist, Roger Penrose[13], casts considerable doubt on the entire idea of inflation! Actually, he is not so much against the inflationary model itself as critic of the initial motivations for the model. He starts arguing that because of the second law of thermodynamics there is an extraordinary degree of precision in the way that the universe must have started in the Big Bang and this according to him presents a profound puzzle. One striking property, to which we have already refereed to, is the observational evidence that the very early universe was in a state of thermal equilibrium as evidenced by the exceptional closeness to the theoretical Planck black body curve of **Fig. 4** at 2.7 K microwave background radiation that represents an actual "flash" of the Big Bang although immensely red shifted by the expansion of the universe. This, according to Penrose, misled some cosmologists to think that the Big Bang was a high entropy or completely random state notwithstanding the fact that because of the second law, it must have been a very low entropy highly ordered state. The great uniformity in the mass of gas and primitive radiation can justify the very low initial entropy of the universe. In effect, we must bear in mind that when we refer to a gas in equilibrium evenly distributed in a volume, we associate it with a state of maximum entropy. However, with gravitating masses the situation is completely different. In this case, a uniform distribution of gravitational particles in a given volume constitutes a state of low entropy and this entropy is increasing when these particles begin to coalesce into groups and eventually reach a single body. In this way, the extremely low entropy of the primitive universe can be explained by the great uniformity it exhibited. An alternative is that the low initial entropy is due to the fact that at some point in its history, our region of the universe experienced a random "*fluctuation"* that took the representative point of this part of the universe in the phase space to a region of entropy extremely low. While this fluctuation is extremely unlikely, it may have occurred. To have an idea of how special the universe must have been at the beginning in order to result in the universe we see now, considering that the number of particles in our visible universe is around 10^{90} it can be estimated that for a closed universe with zero cosmological constant the probability for such an initial low entropy state may be of the order of 1 in $10^{10^{101}}$ certainly an absurdly small probability and this number does not

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[13] Roger Penrose "*The road to reality: A complete g guide to the laws of the universe*" Alfred A. Knopf; New York, 2005.

change much for an infinite universe. So according to Penrose is a fundamental misconception to try to explain the uniformity of the early universe in terms of thermalization as inflation does since this process represents a definite increase in entropy and so the universe would be before thermalization in a more special state than after it.

With reference to the flatness problem, the inflationists claim is that starting from a generic initial state the exponential expansion during the inflationary phase was what served to make the universe so uniform and spatially flat. One essential presumption is that such initial state must be smooth on some very small scale and then this small smooth patch is expanded by inflation. But according to Penrose this need not be so. Fractal sets for example never iron themselves out no matter how much they are stretched so that the generic state from which inflation departs is really not so generic and so inflation to work requires a rather special state and we are back to square one.

One possible way out to these problems is to refer to the coincidence found in the '30s by Dirac that the number of observable particles in the universe (at that time) was of the order of 10^{78}, while the radius of gravitational to electromagnetic forces between two protons is of the order of 10^{39}, that is, the square root of the previous number, which for Dirac should not be a mere coincidence. The problem is that as the number of particles in the observable universe is constantly increasing in proportion to the age of the universe, the only way that the relationship found by Dirac is maintained is that either the force of electromagnetic interaction or the gravitational force changes over time. What Dirac actually suggested is that it is the gravitational force that changes, which so far has not been proven.

Perhaps most interesting, as British physicist John Barrow[14] mentions, is that in 1964 Robert Dicke, of Princeton, pointed out that the coincidence found by Dirac is a numerical relationship on which our own existence depends, since it implies that we live in an era in which the stars have already begun to form helium from hydrogen and the subsequent formation of heavier elements. So, there can only be intelligent observers in a world that has aged enough for this to happen, that is, a world in which the coincidence found by Dirac is fulfilled. This interpretation is a direct application of the *Anthropic Principle*: we can only observe a universe in which this coincidence is fulfilled since otherwise there would be no intelligent observers. According to this principle, the existence of life on Earth and in particular the existence of intelligent life, could not have developed if there had not been an entropy in at least some region of the

[14] J.D.Barrow, F.J.Tipler, *"The Anthropic Cosmological Principle"* Oxford University Press, 1986

universe that was sufficiently low for life evolution. Indeed, the development and evolution of life requires a system far enough from thermodynamic equilibrium to allow all the chemical fluctuations necessary to initiate the first forms of life and their subsequent evolution to take place.

Another problem not completely solved yet refers to inhomogeneities arising during cosmic inflation during which the initial metastable state of the inflation field 'slow-rolls' down the potential to a more stable vacuum. The nature of quantum fluctuations remains controversial. Whilst quantum theory yields probabilistic predictions of the statistics of apparently random individual experimental outcomes, the extrapolation of such statistical structures to the universe in the absence of an experimental context is questionable. It conflicts with Bohr's philosophy according to which quantum phenomena can only be defined and described in a given experimental context. Actually this is one of the reasons that the application of quantum theory to the universe as a whole has always been seen as questionable. However, it remains the use of fluctuations at the microscopic level, following exponential growth in the inflationary period to explain structure formation in the very early universe.

To conclude we see that some very fundamental issues concerning the origin and evolution of the universe (not necessarily only *our* local universe) are still at least to some extent better situated in the realm of metaphysics than in physics. As mentioned at the beginning of this paper, this is probably a temporary situation until hard physical theories take over. However, this shouldn't discourage us to proceed with philosophical speculations since as the history of science and philosophy teaches, this has seldom been a sterile exercise.

Para conocer más:

A guide to reality for the science enthusiast: A rather formal approach to the laws of physics and their philosophy