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The Age of the Universe

Abstract

The belief that the universe as a whole is ageless and unchanging has largely prevailed in human thought since ancient times, with few notable exceptions, and even survived the Copernican and the Newtonian systems. In the 1920's, the pioneering work of Georges Lemaître and Edwin Hubble set the foundations of evolutionary cosmology within the frame of General Relativity. Since then, the concept of cosmic age has entered the domain of physical science, opening up a rich and highly debated motif of modern cosmology. Today the age of the universe is estimated from a variety of independent observational probes. The most accurate measurement comes from recent observations of the cosmic microwave background by the Planck satellite, indicating a cosmic age of 13.8 billion years with an accuracy of $\pm 0.2\%$. This result is consistent with independent lower limits from the age of the oldest known astrophysical objects, such as globular clusters, white dwarfs and low-metallicity stars.

1 Time and Timeless: the Birth of Astronomy

Our perception of the passage of time has been largely shaped by the astronomical environment of our planet. The daily and seasonal rhythms of sunlight and the repeatable motion of the stars in the sky, in contrast with the ephemeral movements of earthly objects, were essential for our ancestors to develop a notion of duration and time flow. While Sun-related periodicities were most apparent, it was probably the Moon, with its mysterious recurring phases, that most deeply fascinated early sky watchers.¹ The emergence of agricultural societies and the development of navigation made astronomical time measurements even more crucial. The Babylonians and the Egyptians carefully recorded the movements of stars and planets for millennia, producing some of the first precise calendars complete with seasonal and lunar phases, even including prediction of eclipses. The stability of the sky was a reassuring mystery. The brightness and relative positions of the stars did not change for countless generations.

¹ A number of archaeological records suggest that the lunar cycle was observed in the Upper Paleolithic by several independent human groups (e.g., Marshack 1991, Barrow 1995).

The silent and perfectly repeatable trajectory of celestial objects was clear evidence of their divine nature. So, while astronomical motions stimulated early measures of time, the sky as a whole was perceived as timeless.

Remarkably, although the cosmic dance of stars and planets was lacking any hint of time direction, nearly all ancient civilizations developed some legendary accounts for an *origin of the world*. These were stories populated by innumerable gods and goddesses, whose births were intertwined with the creation of earthly creatures.² It is unclear to what extent these myths were thought to refer to some historical past, but in some cases, it is possible to speculate on the age of the world according to the different traditions. For the Egyptians, based on the age of their first god Ptah, the world would be 50,000 to 150,000 years old, depending on interpretations.³ The Sumerian cosmos, as reconstructed from the ancient Sumerian King List, was as old as 400,000 years (See *Van De Mieroop (2004)*).⁴ Greeks and Romans hardly mentioned any creation date.⁵ Censorinus, starting up his history of the world, modestly stated: “If the origin of the world had been known to man, I would have begun there”.⁶ Interestingly, however, even peoples advanced in astronomy such as the Babylonians developed their mythical cosmogonies with no reference whatsoever to observed astronomical phenomena. Once created, the physical universe was imagined to remain perfectly changeless.

Two notable exceptions are worth mentioning. The first is the Hindu tradition, which held time itself to be cyclic. Hindus did not contemplate a single creation event, but an everlasting cosmic cycle with a succession of global deaths and rebirths. They extrapolated the regular patterns observable at human

² Most Mesopotamian cultures in the period 3000–1000 BC developed creation myths with significant similarities (Kragh 2007, 7–13). The Egyptians, for example, held that *Geb*, the god of the earth, and *Nut*, goddess of the sky, were originally united, and that the world was formed when their bodies were separated by *Shu*, god of the air and of the atmosphere. This separation initiated the proliferation of living creatures and human beings, together with a complex hierarchy of deities of different ranks. The world was shaped from a primordial substance, a limitless expanse of a waters—likely a reminiscent of the life-bearing inundations of the Nile.

³ According to Diogenes Laërtius, the Egyptians believed that Ptah lived 48,863 years before Alexander the Great (Verbrugge and Wickersham 2001), thus dating the creation 49,219 BC; Theophilus of Antioch, on the other hand, reported an age for the Egyptian cosmos of 153,075 years (Grant 1958).

⁴ However, it has been argued that these ages should be understood in units of lunar cycles rather than years, thus making the age of the Babylonian universe in line with the Egyptian tradition (Olson 1995).

⁵ Greek and Roman scholars traditionally identified the first era of history as the “obscure” *ádelon* period, but did not attempt a systematic dating of its beginning.

⁶ Censorinus, *De Die Natali*, Chapter 1.

scale by huge factors and conceived an amazingly wide range of time units, spanning from microseconds to billions of years.⁷ In their view, the stability of the sky was not evidence of a static universe, but a sign of how insufficient our human condition is to appreciate the reality of the mutable cosmos.

A second exception were the Jews. While their image of the physical universe was very much in line with other middle-eastern cultures of the time,⁸ their notion of *creation* was radically different. The intricate genealogy of gods and semi-divine beings typical of polytheistic religions was sharply contrasted by the free act of a unique and personal God. The *beginning* of the first verse of Genesis⁹ was not simply temporal, but ontological. Creation was not shaping something out of some primordial substance, rather, it was meant as calling into being every creature. All material things were considered ephemeral and contingent. Nothing, even the whole universe, was understood as absolute and self-sufficient: The heavens will vanish like smoke, the Earth will wear out like a garment (Isaiah 51, 6). Cosmic time was seen as limited, both in the past and in the future. According to ancient Jewish chronologies, the creation of the world dated back 4339 BC or 3761 BC, depending on tradition¹⁰. Later on, the medieval Christian culture would inherit the Jewish vision of time, and the world beginning was believed to be between 5300 and 5500 BC.

2 Greek and Medieval Spheres

Mesopotamian and Egyptian astronomers, while unmatched in observational skill, did not reach—and perhaps never sought—a geometrical synthesis of celestial motions. This step was to be taken by the ancient Greeks. The prevailing Aristotelian school held that the perfect repeatability of the motions of the stars demonstrated their superior nature. Any change or irregularity was consid-

7 A single global period (one day and night of Brahma) is about 8.64 billion years long, remarkably close to the order of magnitude the age of the universe according to present-day scientific cosmology. But even such a Brahma day-night period is but a sub-cycle of a much longer era of cosmic death and rebirth, comprising 100 “cosmic years”, each composed by 360 “cosmic days”. Thus, the time elapsed since the start of the current Brahma creation is about 3.1×10^{14} years (22,000 times larger than the age of the universe based on contemporary science). See *Teresi (2003)*.

8 A detailed reconstruction of the universe according to the Old Testament was done by Schiaparelli (1905).

9 “In the beginning God created the heavens and the earth” (*Genesis* 1,1).

10 The date 3761 BC marks the start of the traditional Hebrew Calendar since the 4th century AD.

ered a symptom of incompleteness. The universe was ageless and its natural order was eternal. The divine nature of celestial bodies implied that they were perfectly spherical and made of an everlasting pure substance. Their trajectories could only derive from combinations of *circular and uniform* motions, i.e., motions without beginning nor end. Therefore, not only the universe as a whole, but also every single movement in the sky was eternal. This was equivalent to requiring that *time* be marginalized from the celestial world. Beyond the outer boundary of the *primum mobile*, Aristotle believed that “there is neither place nor void nor time” (Aristotle, *De Caelo*, I, 9). The outer edge of the universe was also the end of time.

The most refined version of Aristotle’s cosmos was the Ptolemaic model, completed around 150 AD.¹¹ It was an ingenious and sophisticated geometrical structure combining a vast number of nested spheres, capable of accurately accounting for *all* celestial trajectories observable by naked eye. It remained the standard model of the universe for fifteen centuries. The medieval cosmos largely inherited the spatial structure from the Ptolemaic model. However, the notion of time was taken from the Jewish tradition. Time, as any other creature, was regarded as finite and contingent. In his *Confessions* (ch. XI and XIII) St. Augustine pointed out that it is impossible to conceive a time that is not part of God’s creation.¹² Furthermore, Thomas Aquinas made an explicit distinction between *creation* and *beginning* of time.¹³ In his notion of *creation ex nihilo* he affirmed creation as the radical, ontological dependence from God of every creature, including time and the universe as a whole (see Carroll 2013). Coherently, he concluded that even an everlasting cosmos would be a created universe just as one with a finite age.

Conceiving time as finite and the universe as contingent, the English Franciscan scholar Robert Grosseteste was inspired to think of something that would have horrified Aristotle. Relying on the principles of Scholastic physics, around 1220 he developed an account of the formation of the Ptolemaic universe

11 In the *Almagest* Ptolemy introduced secondary motions (epicycles, eccentric, equant) which made the model quite intricate. The equant (*punctum equans*) was an off-center point about which the epicycle moved with uniform *angular* velocity, thus representing some compromise with the founding principle of the model.

12 Also, in *The literal meaning of Genesis* (Book 4, Ch. 20, n. 37), where he states: “A period of time is concreated with creatures subject to time, and hence it is also undoubtedly a creature. For there are not and there could not have been and never can be any periods of time that God did not create”.

13 “Things are said to be created in the beginning of time, not as if the beginning of time were a measure of creation, but because together with time heaven and earth were created” (St. Thomas Aquinas, 1997, Q46, 3, 456).

in time.¹⁴ He suggested that an initial seed of light *instantaneously* propagated into an expanding sphere, thereby giving rise to *spatial extension* and starting a physical process *in time*. Interestingly, light was conceived of a more fundamental nature than space and time. Matter was dragged by the expanding light, thus decreasing in density. Since according to Aristotelian physics vacuum is impossible, there has to be a lower limit of possible densities. Grosseteste thought that when the expanding sphere was maximally rarefied, it stabilized to form the outer cosmic boundary. Then every part of the newly formed sphere became a source of light propagating towards the center. Matter was again dragged by the light front, reaching a new limit of rarefaction and producing a second sphere (that of Saturn). Similarly, by means of successive light fronts emanating inwards, all other spheres were formed, completing all the orbs of the Aristotelian universe.

While Grosseteste's cosmology may appear naïve to us, it represents a rare early attempt to describe the development of a finite-age universe based on a conceptually coherent physical system.

3 Newton and the Darkness Paradox

The most revolutionary aspects of the Copernican vision concerned the periphery of the universe, rather than its center. As the movements of the stars were explained in terms of Earth's motions, the lack of any measurable parallax soon required stars to be placed at huge distances, floating in boundless space. The Greek principle of circular uniform motion was still maintained by Copernicus, but was soon destroyed by Kepler's three laws of planets motion. The advent of Newtonian physics eventually consolidated the concept of absolute space and time. As he wrote: "Absolute, true, and mathematical time, of itself, and from its own nature flows equably without regard to anything external" (Newton 1846, 77) and similarly for space.

The extraordinary success of Newton's universal laws seemed to establish the definitive cosmic framework, convincing in its simplicity and prediction power. More than ever, time played the role of an inflexible and eternal axis. The Newtonian universe was spatially infinite in all directions, everywhere filled with stars and subject to the same physical laws, without temporal beginning nor end. However, an annoying detail was disturbing the picture: in such uni-

¹⁴ The cosmological vision of Grosseteste is found in his works *De Luce*, *De motu corporali et luce* and *Hexameron*. For some more discussion, see Bersanelli (2012).

verse the night sky can't be dark. This remarkable circumstance, first noted by Kepler and occasionally discussed by astronomers along the centuries,¹⁵ is quite simple to see. Since the luminosity of a star scales as the inverse square of the distance, $\phi \propto 1/r^2$, and the number of stars in a thin spherical shell at distance r grows as $n \propto r^2$, the luminosity contributed by each shell is $L \propto n\phi = L_0$, independent of distance.

As a consequence, in an infinite and eternal universe the overall luminosity of the sky would diverge and reach everywhere the brightness of the sun. Interestingly, the first appropriate suggestion of a way out of this dilemma came not from a scientist, but from an artist and writer. In 1848 Edgar Allan Poe suggested that the paradox would be solved by “supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us at all” (Poe 1848, 62). The darkness of the sky would be explained if the universe itself had a finite age.

4 Towards a Beginning of Time

The vision of an ageless universe was about to crumble at the beginning of 20th century. Between 1912 and 1924 Vesto Slipher, from Lowell Observatory, Arizona, measured the spectra of 41 spiral nebulae, enigmatic faint diffuse objects whose nature was much debated at the time, and found that nearly all of them showed a well-measurable shift towards longer wavelengths, or *redshift*. Interpreted in terms of Doppler effect, this observation implied that those objects were receding with velocities of several hundred km/s, much larger than typical stellar or planetary velocities. Something weird was going on. In the early 1920's Edwin Hubble, at Mount Wilson Observatory, using an ingenious method based on a particular class of variable stars called *Cepheids*,¹⁶ was able to estimate the distance of a few spiral nebulae. He found that they were as far as a million light years or more,¹⁷ demonstrating that they are indeed external galaxies similar to our Milky Way.

15 The darkness of the night sky became known as “Olbers’ paradox”. A full account is given in Harrison 1987.

16 The use of Cepheids as distance indicators, discovered in 1912 by Henrietta Leavitt, is still crucially important today. Cepheids variables are a specific class of pulsating stars that vary regularly in brightness with a period that correlates with their intrinsic luminosity. Once calibrated, measurements of the period allow astronomers to derive their brightness and, combined with the flux received on Earth, to derive their distance.

17 Today the distance to M31 is measured to be about 2.5 times more.

By 1929 Hubble had measured the distance of several galaxies of Slipher's sample, whose redshift was known, and by correlating their distance d with recession velocity v , he famously found evidence of a linear relationship, $v_r = H_0 d$, where H_0 is known as the *Hubble constant* (Fig. 1). Although Hubble himself was cautious about attaching a strong cosmological meaning to this result,¹⁸ his finding was about to change our cosmic vision. Not long before, in 1916, Albert Einstein had published his theory of General Relativity, whose cosmological solutions could naturally explain the observed recession velocities. General Relativity predicts a dynamic space, either expanding or contracting, with an evolution controlled by the gravitational content of the universe. However, Einstein was not prepared to recognize an evolving cosmos. In 1917 he introduced an additional term in his equations, without violating their mathematical coherence, and attributed to this “cosmological constant” precisely the value required to restore a static space.

However, Einstein's solution turned out to be unstable. Before Hubble's empirical discovery, the Russian physicist Alexandre Friedmann and the Belgian cosmologist Georges Lemaître, independently derived a family of relativistic solutions for an expanding universe (Fig. 1). Lemaître in particular, who was well aware of Slipher's redshift measurements, went beyond and using the available data found evidence of cosmic expansion two years before Hubble's result.¹⁹ Although based on less accurate data, he correctly interprets the redshift of galaxies as due to cosmic expansion, as opposed to a classical Doppler effect within a static Newtonian space.²⁰

Lemaître realized that if we live in an expanding universe, then its average matter-energy density must decrease and the universe as a whole may be subject to a dramatic evolution history. By extrapolating back enough in the past, the density of the universe would reach extremely large values. By 1931 he was convinced that the expansion we observe today should indeed be regarded as the aftermath of such an early, ultra-compact phase, that he called the “primeval atom”. For those who were ready to take seriously this possibility, the question would naturally arise: when did cosmic expansion begin? And can we observationally constrain such primordial era? In Lemaître's vision, for the first time, the concept of an *age of the universe* became an element within a solid physical

18 See, e.g., Luminet 2014 and references therein.

19 Lemaître (1927) assumed the visual brightness of galaxies as distance indicator, which introduced a large spread in his data points.

20 In recognition of Lemaître's fundamental contribution in 2018 the IAU decided to rename the expansion law, traditionally known as Hubble law, as “Hubble-Lemaître law”.

Fig.1: Left: The plot by Hubble (1929) showing the first solid evidence of linear correlation between recession velocity and distance of galaxies. Right: A family of solutions for the expansion history of the universe, as calculated by Lemaître (here, the horizontal axis is cosmic time, the vertical axis is an expansion scale factor).^{a)} Lemaître Archive, manuscripts (1927), Louvain University.^{a)} Lemaître Archive, manuscripts (1927), Louvain University.

theory—General Relativity—and, at least in principle, subject to experimental verification.

Assuming that the expansion rate did not change much in the past, a crude estimate of the age of the universe t_0 can be inferred as the inverse of the Hubble constant, $t_0 = v_r/d = 1/H_0$. The sample of galaxies measured by Hubble yielded a value $H_0 \approx 500 \text{ km s}^{-1} \text{ Mpc}^{-1}$, which corresponds to $t_0 \approx 1.8 \times 10^9 \text{ yr} = 1.8 \text{ Gyr}$.²¹ Lemaître's estimate resulted in an even younger universe, $t_0 \approx 1.4 \text{ Gyr}$. These cosmic ages, however, were too short to be true. The conflict was not with other astronomical observations, but with geological data.

In 1927 Arthur Holmes, a pioneer in the measurement of rock ages from uranium-lead radiometric dating, showed the age of the Earth to be at least 3.0 Gyr.²² And of course, no object in the universe can be older than the universe itself! Lemaître was aware of this problem and considered in his relativistic solution a non-zero cosmological constant,²³ with a generic small value, as he realized it would have the effect of increasing the present age of the universe. Lemaître's defense of the cosmological constant, however, was mostly ignored and set aside until recent times.

²¹ This means that for every mega-parsec (Mpc) in distance the recession velocity increases by 500 km/s. A parsec (pc) is 3.26 light years. The unit Gyr (giga-year) is a billion years.

²² See Dalrymple 2004, 52.

²³ This is the same parameter that Einstein initially introduced with an *ad-hoc* value in his attempt to keep the universe static. Later on, Einstein claimed that introducing the cosmological constant was “the worse blunder of his life”, and since then most cosmologists assumed that it is simply zero.

The cosmic age dilemma contributed to some skepticism against the concept of a finite-age universe by most eminent scientists in the field. Sir Arthur Eddington stated that “Philosophically, the notion of a beginning of the present order of nature is repugnant to me... I should like to find a genuine loophole” (Eddington 1931, 447–453). The fact that Lemaître was a catholic priest raised suspicion that his idea of a *primeval atom* may be forced in by his religious belief. However, while it’s likely that Lemaître’s philosophical background made him prepared to such a possibility, he was never driven by theological prejudice but by scientific evidence (Lambert 2015). Einstein, in particular, was quite reluctant to consider cosmic expansion, let alone a beginning of the universe. When he met Lemaître for the first time at the 1927 Solvay Conference, after some appreciation for the mathematical results of the Belgian priest, he bluntly concluded that, however, “from the physical point of view, [those results] appeared completely abominable”; and in a letter to Dutch cosmologist Willem de Sitter he wrote “This circumstance [of an expanding universe] is irritating... To admit such a possibility seems senseless” (Lemaître 1958, 129–132).²⁴

Recently, an unpublished work by Einstein was uncovered which further confirms his aversion to an evolving universe (O’Raifeartaigh et al. 2014; Castelvocchi 2014). In 1931, as the observational evidence of expansion gained strength, Einstein conceived a cosmological solution in which the expansion was counter-effected by the creation of new matter from empty space, in such a way that the global average density would remain unchanged in time. This work was never published. Almost two decades later, a conceptually similar scenario was independently proposed by Fred Hoyle, Herman Bondi and Thomas Gold, named “steady state” model (Hoyle 1948; Gold 1948), which rivalled the ‘Big Bang’ scenario up to the early 1970’s. The theory was openly motivated by philosophical and aesthetic preference for a homogeneous and isotropic universe with no beginning and no change—the so-called “Perfect Cosmological Principle”—and was capable of sound specific falsifiable predictions (Kragh 2007, 184–200). In these *stationary* cosmologies the flow of time would drive all sorts of processes on local scales, but the universe as a whole, though expanding, would not have any beginning, thus radically solving any age issue.

Indeed, besides philosophical inclinations, the “young” universe problem required a scientific explanation. In the 1940’s the dilemma got worse, as thermonuclear reactions were recognized to be the energy source of stars and placed stellar ages up to several Gyr. Finally, in the 1950’s the fog started to dissipate. It was realized that the Cepheids and other standard candles that Hubble used to

²⁴ See also Luminet (2014) and references therein.

measure galaxy distances were affected by systematic calibration errors.²⁵ That bias led to an overestimate of H_0 by a factor ~ 3 , and to a corresponding underestimate of the age of the universe. Allan Sandage (Tammann and Reindl 2012) greatly improved the techniques to measure distances and in the early 60's he obtained values for H_0 between 75 and 100 km s⁻¹Mpc⁻¹. The age of the universe was now in the range 10 to 13 Gyr, compatible within uncertainties with geological and astronomical limits.

The fascinating and fruitful debate between finite-age and age-less universe reached a definitive turning point in 1965, when Arno Penzias and Bob Wilson at Bell Labs, New Jersey, serendipitously discovered a background of microwave photons coming from every direction of the sky with a temperature²⁶ of ~ 3 K. Robert Dicke's cosmology group at nearby Princeton University readily interpreted the radiation as a remnant of the primordial hot universe.²⁷ Within a decade or so, further observations confirmed that the radiation had the main features expected for a field of fossil cosmological photons. As we shall see, this ancient light, called *cosmic microwave background* (CMB), not only provided a definitive evidence that we live in a historical universe, but since then it has offered a unique opportunity to measure cosmic age to unprecedented precision. To see how that is possible, we have to consider in some more detail how gravity affects cosmic expansion.

5 Gravity vs. Expansion

Estimating the age of the universe as the inverse of the Hubble constant assumes that the expansion rate has remained constant in the past. But is this a realistic assumption? And how can we tell? Here is where General Relativity demonstrates its amazing power. As Lemaître first understood, expansion is a property of space itself, not a motion of galaxies within a static space. Cosmic expansion

25 It was realized that there are two classes of Cepheids, with different period-luminosity correlations. The local Cepheids used by Hubble to calibrate the correlation were systematically fainter than those in external galaxies, which resulted in an overestimate of their distance. Furthermore, for some of the most distant galaxies, star clusters were confused with individual stars, further contributing to an overestimate of H_0 .

26 In radio and microwave astronomy it is convenient to express electromagnetic brightness in terms of the temperature of an equivalent blackbody source.

27 The key original discovery papers are Penzias and Wilson 1965; Dicke et al. (1965). Penzias and Wilson received the Nobel Prize in 1978 for their experimental discovery. Jim Peebles's Nobel Prize in 2019 was largely in recognition of his theoretical work in the interpretation of the CMB. For a complete historical account see Peebles, Page and Partridge (2009).

is quantified by an adimensional scale factor, $a(t)$, which is normalized so that its present value is unity, $a(t_0) = 1$. A universe that expands at a fixed rate is simply described by $a(t) = H_0 t$, and its age is $t_0 = 1/H_0$. Gravity, however, makes things much more interesting. According to Einstein's field equation, expansion is influenced by gravitational effects produced by the different matter and energy components that are present in the universe. The total matter-energy density, Ω_0 , can be expressed as the sum of in three terms:

$$\Omega_0 = \Omega_R + \Omega_M + \Omega_\Lambda$$

The first term, Ω_R , is the energy density of radiation, which includes photons and relativistic particles such as neutrinos. The second term, Ω_M , includes ordinary baryonic matter (the stuff that makes stars, planets and ourselves) as well as dark matter.²⁸ The third term, Ω_Λ , dubbed “dark energy”, incorporates the energy density associated with a non-zero cosmological constant. General Relativity shows that the value of Ω_0 determines the global curvature of space, so it's convenient to normalize these parameters so that $\Omega_0 = 1$ corresponds to a zero-curvature (Euclidean) space. The three contributions $\Omega_R, \Omega_M, \Omega_\Lambda$ change in different ways with the scale factor $a(t)$ and therefore become dominant at different epochs of cosmic history. Radiation has the fastest decrease, proportional to a^{-4} , thus it dominated in the young universe but it rapidly became negligible. Then matter density (which scales as a^{-3}) took over, and the universe entered the phase when local gravitational collapse was able to form galaxies, stars, planets, opening the way to the complexity we see and experience today. Finally, the term Ω_Λ is independent of the expansion rate. Therefore, a positive value of Ω_Λ , even if small, at some point will make dark energy the dominant form of energy with the effect of accelerating the expansion.

General Relativity shows precisely how the density parameters, combined with a value of the Hubble constant, determine the function $a(t)$. Fig. 2 shows a few solutions for $a(t)$, assuming a fixed value of H_0 . The age of the universe is the intersect of each model curve with the horizontal time axis. The red line corresponds to an ideal ‘empty universe’, in which all density parameters are set to zero. In this case of course gravity has no effect, the expansion rate is constant and $t_0 = 1/H_0$. For any non-zero choice of the density parameters the expansion is influenced by the gravitational effect of the respective mass-energy

²⁸ There is strong observational evidence that about 80% of the matter contributing to the gravitational fields of galaxies and clusters of galaxies is in some form of non-baryonic particles, called “dark matter”, whose nature is yet unknown.

Fig. 2: World models for a given value of the present expansion rate (the Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$) and for different choices of density parameters ($\Omega_R = 0$ for all models, while the values of Ω_M and Ω_Λ are shown in the plot). The red linear model is an empty universe ($\Omega_R = \Omega_M = \Omega_\Lambda = 0$) for which cosmic age is simply the inverse of the Hubble constant (shown in blue).

contributions, resulting in different cosmic ages. For example, if $\Omega_R = \Omega_\Lambda = 0$ and $\Omega_M = 1$ (the so-called “Einstein-De Sitter Model”), calculation shows that $t_0 = 2/(3H_0)$. Higher values of matter density lead to shorter cosmic ages. In the case shown ($\Omega_M = 6$, with $\Omega_R = \Omega_\Lambda = 0$) gravity is strong enough to win over expansion and the universe will eventually contract and collapse in a finite time in the future. Note that the effect of $\Omega_\Lambda > 0$ is to introduce an acceleration at late times (dotted curve), which implies an *increase* of the present cosmic age.

In general, it is convenient to express the age of the universe as the inverse of the Hubble constant times a factor, f , which incorporates the gravitational effects of the density parameters:

$$t_0 = \frac{1}{H_0} f(\Omega_R, \Omega_M, \Omega_\Lambda)$$

General Relativity specifies the function f , as shown here for completeness:

$$f = \int_0^1 da \left(\frac{\Omega_R}{a^2} + \frac{\Omega_M}{a} + a^2 \Omega_\Lambda - (\Omega_0 - 1) \right)^{-1/2}$$

The values of the four free parameters—Hubble constant and the three density parameters²⁹—is not fixed by the theory. If we are able to accurately measure their values, then the age of the universe can be derived with a comparable accuracy.

In the mid 1990's a number of studies of galaxies distribution suggested a value $\Omega_M \approx 0.3$, corresponding to an open universe with $t_0 \approx 12$ Gyr. Although the uncertainties were large, such cosmic age was hardly compatible with the age of some old stellar clusters (Spergel et al. 1997),³⁰ measured to be 13–14 Gyr. Cosmology seemed to enter another embarrassing age crisis. Quite timely, however, another unexpected discovery came on stage. Two independent groups using a specific class of distant Supernovae as standard candles,³¹ realized that the present expansion rate is *higher* than it was a few billion years ago (Perlmutter et al. 1999; Riess et al. 1998).³² In other words, cosmic expansion is *accelerating*, which implies a positive value of Ω_Λ (Fig. 2). Their fit to relativistic models suggested $\Omega_M \approx 0.3$ (compatible with previous estimates) and $\Omega_\Lambda \approx 0.7$. The discovery that $\Omega_\Lambda > 0$, a possibility nearly forgotten since the times of Lemaître, was a major surprise for the physics community at large. The effect on the age of the universe was an increase by ~ 2 Gyr, thus resolving the age tension with globular clusters.

A coherent picture seemed to emerge, but the measurement uncertainties were very large, over 30%, and the issue of cosmic age was still wavering. Since then, observations of the relic CMB photons have played a central role in pinning down the value of the cosmological parameters, including those controlling the age of the universe.

6 Cosmic Age and Cosmic Edge

The discovery of the CMB transformed the bold hypothesis of an initial hot state of the universe into a unique observational opportunity. The primordial hot and compressed plasma progressively cooled and rarefied under the effect of expansion. After about 380,000 years, when the temperature dropped below ~ 3000 K, neutral atoms could form from the primordial mixture of electrons and light nu-

²⁹ The total density Ω_0 is just their sum.

³⁰ We will come back to age of globular cluster later in this work.

³¹ These were a specific class of exploding stars, called Supernovae type-Ia, which result from very repeatable process and therefore present a nearly standard peak luminosity which can be used to infer the distance of the host galaxy.

³² The discovery led to the 2011 Nobel Prize to Saul Perlmutter, Brian Schmidt and Adam Riess.

clei (essentially hydrogen and helium). As matter became electrically neutral, suddenly the universe became transparent to light and the CMB photons could freely propagate. At that time, known as ‘recombination epoch’, the wavelength of the photons was $\sim 0.5 - 1$ micron, i.e., in the visible to near-infrared. Since then, the expansion has stretched their wavelength by a factor $z \sim 1100$, shifting them into the microwave range ($\sim$ few mm). The low energy of the relic photons, combined by the finite age of the universe, fully explain the darkness paradox.

We see the CMB emerge from a sort of cosmic photosphere, called “last scattering surface”, surrounding us near the edge of the observable universe. Such space-time surface represents a physical barrier to direct observation with light, as beyond that limit the universe is opaque to electromagnetic radiation.³³ Despite the enormous number of galaxies, the voids between them are huge and the CMB traveled nearly unperturbed for almost the whole cosmic time, bringing to us a remarkably faithful image of the last scattering surface.

Since its first discovery, the CMB has been a generous source of cosmological information. Its thermal origin is brilliantly confirmed by its purely blackbody spectrum, measured to exquisite precision (Mather et al. 1994) at a temperature $T_0 = 2.725 \pm 0.001$ K. The corresponding radiation energy density³⁴ turns out to be, $\Omega_R \approx 10^{-4}$, which is very small compared to the other density parameters. As a consequence, the gravitational effect of radiation can be ignored in the calculation of the factor f , a welcome simplification in our attempt to measure the age of the universe.

The CMB intensity is highly isotropic, but not completely. This was expected because, in order to explain the formation of galaxies and of other cosmic structures under the action of gravity, primordial density perturbations needed to be present at the last scattering. Since the CMB photons are influenced by the gravitational potential, their intensity traces the early density perturbations and must appear to us as temperature differences from one direction to another in the sky. In 1992, NASA’s COBE satellite first detected such CMB *anisotropies*³⁵ at a level of 0.001 % at all angular scales larger than $\sim 7^\circ$. In 2000, NASA launched the

33 In some future, we might be able to detect the background of low-energy cosmic neutrinos, which cross unimpeded the hot primordial plasma and reach us directly from a universe only ~ 1 s old. And if primordial gravitational waves could be measured, these would get us a directly to a tiny fraction of a second of the beginning.

34 The radiation density parameter includes also the contribution of neutrinos, about 68% of the photon energy density.

35 The discovery of CMB temperature anisotropies and the high precision measurement of the CMB frequency spectrum obtained by the COBE satellite in 1992 granted the 2006 Nobel Prize for Physics to George Smoot and John Mather. See: Smoot et al. (1992); Mather et al. (1994).

WMAP satellite³⁶ which obtained full-sky maps of the CMB fluctuations with sub-degree angular resolution and much improved sensitivity. The Planck satellite, launched in 2009 by the European Space Agency, represents the current state of the art of full-sky CMB observations.

The amplitude of CMB anisotropies at different angular scales depends on the physical conditions in the hot primeval medium, as well as on the geometry of the expanding space in which the photons have travelled to reach us. For this reason, CMB anisotropies encode a wealth of cosmological secrets that can be unveiled by accurate, high resolution measurements. The fundamental statistical information contained in a CMB map is captured by the so-called “angular power spectrum”, a spherical harmonic expansion of the measured temperature fluctuations in the sky. The power spectrum quantifies the amplitude of the anisotropy as a function of angular scale θ , or multipole $\ell \sim 1/\theta$. On scales below $\sim 1^\circ$, primordial fluctuations were processed by acoustic oscillations driven by gravity and photon pressure in the baryon-photon fluid. The oscillations that happened to be in maxima of compression or rarefaction at the time of decoupling, produce peaks in the anisotropy power at specific angular scales. Therefore, the theory predicts a characteristic harmonic pattern (Fig. 3) whose details are very sensitive to the physical characteristics of the primordial plasma, including the value of the density parameters and of the Hubble constant. In turn, accurate measurement of the CMB can be used to extract the value of those parameters.

7 The Very First Light

The precise measurement of the main cosmological parameters was one of the key scientific objectives of the ESA Planck satellite,³⁷ launched by an Ariane 5 rocket from the launch pad in Kourou, French Guiana, on 14 May 2009. The satellite took data uninterruptedly for four years, scanning the sky from an especially suitable orbit at 1.5 million km away from Earth. The telescope, instruments and observing strategy were designed to reach an unprecedented combination of angular resolution (up to 0.1°), sky coverage (100%), wavelength range (from 0.3 to 10 mm), sensitivity ($\Delta T/T \sim 10^{-6}$), calibration accuracy ($< 0.1\%$). Local astrophysical emissions contribute to the observed microwave signal and must be accurately removed. The extreme sensitivity of Planck called for pre-

³⁶ For the excellent WMAP results see Bennett et al. (2013) and references therein.

³⁷ <https://www.cosmos.esa.int/web/planck>.

Fig. 3: CMB temperature angular power spectra, showing the sensitivity to the value of density parameters that control the age of the universe (adapted from Hu and Dodelson 2002, with permission from the Authors).

cision measurement not only at wavelengths dominated by the CMB ($\sim 3\text{--}4$ mm), but also in spectral bands where the foregrounds are strong. To cover such wide wavelength range, two complementary instruments were developed, using radiometric and bolometric detectors in their best windows of operation, cooled to cryogenic temperatures.³⁸ The two instruments shared the focal plane of a 1.5-m off-axis telescope (Fig. 4). The ambitious performance of Planck was verified in a demanding ground calibration campaign before launch, and has been wonderfully confirmed by in-flight data.

To calibrate the CMB maps, Planck (as well as WMAP and COBE/DMR) used the effect of the proper motion of our local rest frame with respect to the CMB itself. In fact, as for any other cosmic observer, our local motion produces by Doppler effect a slight increase of the CMB temperature in the direction of our velocity vector, and a symmetric decrease in the opposite direction.³⁹ Interestingly, therefore, the CMB represents a natural global rest frame to evaluate the local velocity of any cosmic observer relative to the expansion flow. This philosophically intriguing circumstance has also the very practical advantage of providing a nearly perfect calibrator for CMB observations.

³⁸ For an overview of the results of the Planck mission see Planck Collaboration (2018a). The satellite and the two Planck instruments are described in Tauber et al 2010; Bersanelli et al. 2010; Lamarre et al. 2010).

³⁹ Planck measured a dipole anisotropy with an amplitude of 3.362 ± 0.001 mK corresponding to a velocity 369.82 ± 0.11 km/s, in the direction of a precisely identified point (± 0.6 arcmin) in the constellation of Leo (Planck Collaboration 2018a).

Fig. 4: Left: the Planck satellite during system ground tests, just before launch. Right: a view of the Planck focal plane, including two integrated instruments: Low Frequency Instrument, operating in the 30–70 GHz bands, and the High Frequency Instrument, covering the 100–850 GHz range. (Credit: ESA, ASI, CNES).

The final analysis of the Planck data has been recently completed (Planck Collaboration, 2020a-b). The Planck data also include polarization and gravitational lensing, which provide further leverage to extract cosmological parameters. Fig. 5 shows the full-sky map of temperature anisotropies after removal of the foreground emissions. The corresponding angular power spectrum is shown in Fig. 6. The blue solid line is the best fit to the simplest cosmological model, which includes six degrees of freedom encoding the values of cosmological parameters. The red points are the Planck data. Here one can appreciate the amazing agreement between the experimental data and the theoretical model. The Planck results on polarization and lensing beautifully confirm the best fit parameters and help break internal degeneracy.

The six-parameter fit yields a Hubble constant of $67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$, somewhat lower than previous estimates based on traditional methods. The matter energy density⁴⁰ gives $\Omega_{\text{M}} = 0.315 \pm 0.007$, consistent with previous estimates but greatly improved accuracy. Allowing the total density as a free parameter⁴¹ provides very stringent limit on curvature, which is further tightened by combining Planck data with recent measurements of large-scale structure, yielding $\Omega_0 = 0.9993 \pm 0.0019$. We seem to live in a very Euclidean universe: even with

⁴⁰ Planck also measured the independent contributions from baryonic and dark matter components, which account for 4.9% and 26.5%, respectively, of the total energy density.

⁴¹ The standard 6-parameters fit assumes a flat geometry ($\Omega_0 = 1$), so fitting for Ω_0 is an extension of the basic model.

Fig. 5: Planck all-sky map of the CMB. Thanks to Planck’s nine frequency bands and to sophisticated analysis techniques, the foreground emissions were accurately subtracted. (Planck Collaboration, 2018. Credit: ESA, LFI Consortium, HFI Consortium).

Fig. 6: Planck power spectrum of the temperature anisotropies of the CMB. The horizontal axis is the multipole number, inversely proportional to the angular scale (left to right: 180 degrees to 7 arcmin). The vertical axis is the anisotropy power in μK^2 . Bottom panel: residuals to the best fit model. (Planck Collaboration, 2018a. Credit: ESA, LFI Consortium, HFI Consortium).

Fig. 7: Values of the function f for different values of dark matter and dark energy density parameters. Highlighted in blue are the values for the “empty universe” ($f = 1$) and for the Einstein-de Sitter model ($f = 2/3$). In red is the value for the best fit model from Planck 2018 data.

< 1% precision we can’t detect any global curvature. The remaining energy density is contributed by dark energy, with $\Omega_\Lambda = 0.685 \pm 0.007$, in agreement with the independent estimate of the accelerated expansion from type-Ia Supernovae, but again with much improved precision. The combination of these results yield an age of the universe of $t_0 = 13.797 \pm 0.023$ Gyr. This level of accuracy ($\sim 0.2\%$) is quite remarkable: it’s like guessing the age of a 50-years-old person with the precision of 1 month.

8 The Oldest Objects in House

These high precision results call for independent crosschecks. Results from previous CMB experiments and other cosmological probes, while less accurate, are generally in good agreement with those of Planck.⁴² Recently, however, improved measurements of the Hubble constant from traditional Cepheid-calibrated red-

⁴² The WMAP data yield a cosmic age fully consistent with Planck, 13.772 ± 0.059 Gyr (Bennett et al 2013), with an uncertainty larger by a factor of 3. Data from galaxy redshift surveys such as 6-degree Field Galaxy Survey (6dFGS) and Sloan Digital Sky Survey Main Galaxy Sample (SDSS MGS) have provided excellent and consistent parameter estimation (Carter et al 2018).

shift-distance methods⁴³ yielded values $\sim 8\%$ higher than CMB-based results (both Planck and WMAP), and of course a correspondingly younger universe, $t_0 \sim 12.7$ Gyr. Whether this tension, significant at ~ 3.5 standard deviations, is a symptom of new physics, or it is due to undetected systematic effects, is the subject of a renewed debate on the value of the Hubble constant.

A radically independent verification may come from the limits imposed to the age of the universe by the oldest stars (Fig. 8). Even a single object older than t_0 would represent a serious challenge. On the other hand, we have evidence that the first stars were born just ~ 0.6 Gyr after recombination (Planck Collaboration 2018a), so we expect the oldest stars to be ~ 13.2 Gyr or ~ 12.1 Gyr old, depending on the scenarios. Exploiting at best our understanding of stellar physics we have an opportunity to test cosmology-based estimates.

How can we identify very old stellar objects? A first way is to look at globular clusters, families of 10^5 to 10^6 stars known to have formed very early on. Astronomers can measure the age of a star cluster by studying their stellar population. Since more massive stars live shorter lives in their equilibrium state (called “main sequence”), by looking at the most massive stars which are still in the main sequence one can infer the cluster age. A recent study of 22 clusters shows ages in the range 10.8–13.6 Gyr with typical uncertainty ± 1.6 Gyr. A detailed work on the cluster HP-1 yields an age of 12.8 ± 0.9 Gyr (O’Malley et al. 2017; Kerber et al. 2019). Independent measures of globular clusters age come from white dwarfs, compact stellar relics slowly cooling down as they radiate their internal heat. A classic study (Hansen et al. 2002) of white dwarfs yield 12.7 ± 0.7 Gyr, fully compatible with main sequence age estimates.

Another age test comes from single, very old stars. We can recognize them by studying their composition. Just after recombination, 380,000 years after the Big Bang, the only elements in the universe were hydrogen and helium, as Carbon and heavier elements (called “metals” by astronomers) would only form in thermonuclear reactions in stellar cores. New stars were continuously born from the ashes of previous generations, with increasing abundance of heavy elements. Therefore, stars with very little “metallicity” must be very old, and astronomers can quantify their age from detailed analysis of their spectra. A study of three sub-giant ultra-low metallicity stars (Vanden Berg et al. 2014) gave ages of 12.08, 12.56, and 14.27 Gyr with an uncertainty of ± 0.8 Gyr.

The latter star (HD140283, known as *Methuselah Star*) at face value has an age even older than the value of t_0 measured by Planck, but well compatible within the uncertainty, while it is somewhat in tension (~ 2.7 standard deviations)

⁴³ These programs used Cepheid-calibrated Supernovae type-Ia (Riess et al. 2018).

with the younger universe implied by the recent Cepheid-based estimates of H_0 . Overall, stellar ages seem to prefer the CMB-driven estimates, but the uncertainties are still too large. Future progress in stellar astrophysics, as well as on other independent approaches⁴⁴ to measure H_0 , will surely contribute to the cosmic age debate.⁴⁵

Fig. 8: *Right:* One of the oldest known objects in the universe. *Left:* The globular cluster HP-1 (Credit: Gemini Obs./AURA /NSF/M. Libralato, STScI). *Middle:* The dimmest stars in the image are white dwarfs in the globular cluster M4 (Credit: HST, NASA and H. Richer, Univ. of British Columbia). *Right:* The low-metallicity star D140283 (Credit: DSS, STScI/AURA, Palomar/Caltech, UKSTU/AAO).

9 A Wonderful Space-Time Vista Point

For millennia the notion of an ageless and unchanging universe has been deeply rooted in human minds. The Aristotelian-Ptolemaic model encoded the vision of an eternal cosmos into a complex geometrical structure that successfully reproduced all visible trajectories in the sky. The Copernican revolution and the establishment of the Newtonian system represented two enormous paradigm shifts, however, neither of them even touched the vision of a globally immutable universe. It is not surprising, therefore, that when theoretical and observational hints of an evolving universe emerged, the transition to the new view was troubled and highly debated, resisted even by some of the very same actors of the new emergent paradigm. The most shocking element was the notion that the universe itself may have a beginning. In spite of Einstein's reluctance his General Relativity, as proposed by Lemaître and Friedmann and combined with observations by Hubble and others, brought the concept of cosmic age into mainstream

⁴⁴ A promising avenue is to use gravitational wave “standard sirens” (Feeney et al. 2019).

⁴⁵ For further discussion, see Jimenez et al. (2019).

science. Since then, evaluating the age of the universe has become an ambitious objective of experimental work. Today, just a century later, observations of the primordial CMB photons have led to an estimate of cosmic age of $t_0 = 13.8$ Gyr with sub-percent accuracy, in good agreement with most independent probes.

The time t_0 is the present age of the universe not only for *us*, but for *any* cosmic observer. Furthermore, the CMB temperature provides a natural *cosmic clock*, in a similar way as it offers a natural reference frame to measure local velocities. As the universe expands, the CMB temperature slowly cools down as $T_{\text{CMB}}(t) = T_0/a(t)$, a known monotonic function of time. This is indeed a very slow clock hand: with our current technology, to appreciate the smallest conceivable temperature drop, say 1 μK , it would take 4,700 years. Of course, we can't wait that long, however, it is possible to measure *now* the temperature of the CMB *as it was in the past*, by indirectly measuring its temperature in regions that are sufficiently far away.⁴⁶ These observations have been carried out and confirm the expected change $T_{\text{CMB}}(t)$, further proving the reality of our evolving cosmic scenario.

Our measurements of cosmological parameters not only determine t_0 , but also the epoch of a number of global events that took place in cosmic history. Going backwards, these include the start of the accelerated expansion ($t \approx 9.8$ Gyr), the formation of the first stars ($t \approx 0.6$ Gyr), photon decoupling ($t \approx 0.38$ Myr), primordial nucleosynthesis ($t \approx 100$ s), electron-positron annihilation ($t \approx 30$ s), decoupling of neutrinos ($t \approx 2$ s), protons and neutrons formation ($t \approx 10^{-4}$ s), and more. In some sense, all these events are present to us *now*, as they are imprinted in space-time layers at different depths into the observable universe. We can't see most of them directly (a notable exception is photon decoupling, beautifully visible to us through the CMB), but in principle they are all out there. Interestingly though, as a direct consequence of cosmic expansion, we would see them to last a much longer time than they actually took for a hypothetical local witness. Indeed, as observations confirm,⁴⁷ the duration Δt of a past cosmic event is observed to last $\Delta t_0 = \Delta t/a(t)$. For example, primordial nucleosynthesis, which lasted ~ 5 minutes, if observed now in the distant universe would appear to last some $\sim 120,000$ years. Seen through our eyes, or through the

⁴⁶ This has been done in two ways: by exploiting the scatter of CMB photons off the hot gas in clusters of galaxies, known as thermal Sunyaev-Zel'dovich effect; and by measuring the excitation by CMB photons of C, CO or CN absorption lines in the spectra of distant quasars (Luzzi et al. 2015).

⁴⁷ Cosmological time dilation was observed in SN Ia (Foley R.J. et al. 2005); and in Gamma Ray Bursts (Zhang et al. 2013).

eyes of any other cosmic observer, time indefinitely slows down as we approach the beginning of time.

In retrospect, it is absolutely remarkable that today we are discussing slight tensions at the few percent level about the age of a 13.8 Gyr old universe. On the other hand, we should not forget that our understanding of the universe is still incomplete, and becomes particularly uncertain when approaching the very beginning of cosmic time. As history has shown, our notion of what we mean by “universe” has deeply changed in different epochs. It is entirely possible that cosmologists of the next century will regard our views as naive steps toward a new and deeper cosmic vision, hopefully incorporating (not rejecting!) what we have learned so far. If some of the current speculations will turn out to be correct, we might be brought back to a new incarnation of the traditional image of an everlasting and ultimately unchanging cosmos;⁴⁸ or perhaps the next revolution in cosmology will be entirely surprising and far from current ideas. But surely for the time being we can enjoy the awesome space-time panorama we have come to understand and contemplate.

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⁴⁸ Examples are some versions of inflation models, such as eternal inflation (e.g., Guth 2007), and new versions of a cyclic models (e.g., Steinhard and Turok 2002).

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