The First Three Minutes

A Modern View of the Origin of the Universe

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I was there! Not during the first three minutes of course, but when the original lecture by Weinberg was delivered in the newly built Science Center back in 1973[1]. I must admit that I did not recall very much of the lecture, except its punchline (absent in the book) that after the first three minutes nothing really interesting has happened in the universe, because by then essentially all the hydrogen and helium - the main material existing in the universe, had been formed. The book was written a few years afterwards (refering to the lecture, not the forming of the hydrogen and helium) and I bought myself a copy back in the summer of 1979. I read it for the first time on a flight back from San Fransisco to New York taken together with my just widowed mother, and fortuitously the last page of the book was written by the author when also flying across the continent back to Boston.

Reading it a second time it makes more of an intellectual impact than when encountered for the first time. You are supposed to be more intellectually astute when young, on the other hand experience and wisdom can usually make up for reduced mental flexibility. And it is notoriously well-known that youth seldom exploits its advantages. Why should it? life is going to go on for ever.

So what is the book really about? Cosmology is really on the border of metaphysics at least as far as it comes to ontology. On the other hand what distinguishes modern cosmology from say the writings of the Edda boils down to epistemology. In essence the book is an exercise in the proverbial back of the envelope calculations, applying some principles of modern physics, especially particle physics, to the status of the early universe. Of course it is speculation, playful speculation, but as all play deadly serious. Weinberg is simply following the time-honored principle, so dear to mathematicians, of making some assumptions and then work out the ultimate consequences to the bitter end. The author proposes that one should not be wary of taking physical theories too seriously, on the contrary the usual problem is to take them not seriously enough. To have an open mind too early on gets you nowhere, there will always be a time of reconsideration if and when contradictions are encountered. So this is the essence of the scientific approach. The long chains of deductive thoughts that have to mesh with independant reality. What ultimately gives conviction is the robustness that can only be achieved by repeated confirmations. This is what makes science so hard, and this is also what is lost in most histories of the science, Weinberg remarks. Whig histories in which the lucky break, the serendipitous

[1] The Undergraduate Science Center built in 1972 became the new site of the Math department vacating from its cramped quarters on 2 Divinity Avenue, and was inaugurated a year or so later by a series of talks aimed at the general public. It could have been then, or maybe a year later, when J.S.Gould also gave a talk.

discovery and the transcendental insight are naturally given pride of place, while the most typical road of scientific activity is paved with lost opportunities.

The basic story is simple. Distant galaxies are running away from us. The visible universe is expanding. And if it is getting larger and larger in the future the logical conclusion is that it was smaller and smaller the further we look back into the past. The universe is not stable. This momentous discovery is due to the careful study of the spectral lines given off by the faint radiation reaching us from distant galaxies and associated with the name of Hubble. The gauging of distances in the universe is by itself an interesting and instructive study based on a chain of assumptions, some of them not a little audacious. It needs not to be told here, and Weinberg also makes only a fleeting reference to it. The remarkable thing is that the expansion of the universe was actually already implicit in Einsteins field equations. Contrary to expectations those implied a non-static universe. Einstein fudged them by introducing a so called cosmological constant, something he lived to regret when the redshift they would otherwise have predicted was experimentally discovered[2]. But the Russian mathematician Friedman had solved the original equation predicting an expanding universe already 1922, and Hubble may very well have known of it, which may have influenced what he was looking for, and especially how to interpret the shift. In retrospect theories that prevail are the ones that are remembered, which, as noted above, simplifies history excessively. The standard interpretation of the redshift was far from uncontroversial at the time, and dissenters within the cosmological community remained for many years to come. But even if you accept the expansion of the universe it does not contradict a steady state[3] universe, one can imagine that matter is continously being created to keep the density of the universe constant. This was a view proposed notably by Fred Hoyle in contrast to the Big Bang view of Gamow[4]. What clinched the matter was the discovery of cosmic background radiation in 1965, and since then the Big Bang theory has become the standard model against which all theories are

[2] The status of the Cosmological constant is fluctuating, at the time Weinberg wrote the book it was discounted. Later on it has had its proponents.

[3] A steady state universe amounts to the universe being temporally homogenous as well as spatially (the cosmological principle ultimately derivable to Copernicus in his claim that the earth occupied no special position). In fact current scientific philosophy at the time favoured time-independance. One is invariably reminded of the geologist Hutton two hundred years ago, who on the history of the earth famously said *I see no vestige of a beginning nor the prospects of an end.* In fact there are two paradigms to the history of the universe. One that there is no history, that the universe is unchanging, or what amounts to the same thing, cyclic. And the other, that there is in fact a beginning and an end, and that everything happens only once, and hence that the moment matters, as it does, or should do, for the individual.

[4] The notion 'Big Bang' is supposed to derive from Hoyle who intended it as a disparagment, but it stuck, and its derisive overtones have long since faded away. At the time assumptions of a big bang was fraught with contradictions, as can be gleaned from the presentation in Hoyles elementary book on Astronomy from the early 60's. In that book he also gives a lot of attention to the Belgian abbé Lemaitre as one of the most vocal proponents of the theory. As noted above the big bang hypothesis squares very well with Genesis, and should have been particularly congenial to Catholic dogma.

compared[5]. Even Hoyle later on admitted defeat and converted to faith in the Big Bang[6].

Speculation is one thing, confirmation another, but of course any confirmation is but provisional as we are being taught by Popper. The nature of confirmation may need to be explained. Confirmation is not the same as confirmation by the senses (seeing is believing), as there is usually no confirmation that does not build on additional assumptions and speculative theories. But the essence of confirmation is instead that totally independent point of views mesh with each other, and it is exactly this that gives us the conviction of there being an outside reality, which we may interpret but never mold[7].

What is puzzling, and refers to the missed opportunities mentioned above, is that the background radiation had not been looked for earlier and discovered. In retrospect that could have been done already in the late forties. In fact, as many cosmologists later would point out, predictions had been made, and even some attempts at empirical testing, although the predicted temperatures were too low (just a few degrees Kelvin) to be thought feasible to measure. One may quibble, but the fact of history is that such matters were not ripe until 1965.

So what are the facts? Distant galaxies are receeding at velocities proportional to their distances. In fact the empirical data available shows no such clear relation. This is due to noise. First there are local variations, our closest galactic neighbour - the Andromeda galaxy, actually displays a blue shift, i.e. it is approaching us[8]. Secondly it is very hard to estimate the distances to galaxies. For those that are close we can use the standard methods of Cepheids[9], but for more distant galaxies one essentially estimates distance by apparent luminosity. And then of course for very distant galaxies, their distances are derived from their red-shifts, following the well-known principle of turning theorems into

[5] Religious Dogma is a well-known notion. In fact any religion worth its salt needs to be dogmatic. In a similar sense science is also dogmatic, there is one truth and only one truth, without which there would be total confusion and progress as we know of it impossible. But while religious dogma at least appears to be arbitrary and fixed, scientific dogmas come in graduations. Dogmas can always be challenged and occasionally overthrown, but then always on grounds of conflicting with an even more fundamental dogma. Underlying it all is the dogma of rationalism, but as Cantors hierarchy of transfinite cardinals illustrates, there cannot be any precise articulation of a fundamental dogma.

[6] I remember reading in the late sixties a note in the newspaper to that effect. Later on, as I have read, Hoyle recanted, but then in later life he became susceptible to many crankish notions. He was a hero of my youth when I was interested in astronomy. Late one night in September 2001, changing trains in Munich en route to Bucharest, I picked up a discarded British newspaper in a wastepaper basket and learned that Hoyle had just died.

[7] Of course we can affect reality, that is what living is after all about, but only its superficial aspects. The laws of nature we cannot ordain, only submit to

[8] Galaxies are rotating quite fast. The sun is rotating in the Milky way about eight times as fast as the earth is rotating around the sun. Thus the shift for nearby galaxies depends on the locations of the stars within. Some you expect would show red shifts other blue shifts. Of course it is elementary to average and come up with the average motion of the galaxy as such. Still the Andromeda as a whole approaches us.

[9] The patient measurement by Miss Leavitt at Harvard Observatory at the beginning of the last century of Cepheids in the Magellan Clouds established the simple relationship between periodicity and luminosity, that has served as the basis for all extra-galactical measure of distances.

definitions. This illustrates that without the underlying theoretical understanding there can be no meaningful interpretation. In fact, as is easily seen, if we postulate that galaxies are receeding from each other and that there are no priviliged positions, than necessarily those speeds must be proportional to distance.

> Small velocities add up with high degree of precision, for velocities closer to the speed of light you need to take into account the relativistic effects (a reparametrisation of the reals using tangens transform relativistic addition to ordinary, but this is of course only a formality). But does this also apply here? Weinberg says so. Is he nodding? In particular can those velocities be larger than the speed of light? After all it is space that is expanding, not the case of particles moving in space. The question is puzzling because this seem to imply that we have a notion of rest with respect to space, and does this not go against the very notion of relativity theory in which there is no notion of rest, only the notion of two systems of reference being in uniform motion with respect to each other.

But from this empirical data it seems impossible to get any reasonably accurate estimate of the Hubble constant[10] so crucial in determining the age of the universe, thus it is not susprising that initial estimates thereof brought about figures significantly short of the age of the Earth itself. But those are secondary concerns, the interesting part is the playing of the game.

First what is meant by the Big Bang. A popular image is that of a ball of fire rapidly expanding in empty space. This of course contradicts the assumption of homogeneity, in particular that no point in space should be priviliged. A common image in popular science is the blowing up of a balloon on which specks are being painted. This means that 3-dimensional space is being expanded inside some virtual ambient space inaccessible to us. Here popular science necessarily is vague, and so is Weinberg. But a competent writer can be vague and still know perfectly whereof he is speaking. Weinberg speaks ingeniously about the typical distance $R(t)$ between two galaxies. If we picture the world as a 3-dimensional sphere, this distance can be thought of as a canonical fraction of the radius of that sphere, in fact the number of galaxies in the universe should be thought of as a characteristic number[11]. In general non-Euclidean geometries come equipped with intrinsic notions of length. For the spherical this is obvious, but what is more startling is that it also makes sense for the infinite Hyperbolic space. Thus in the non-Euclidan setting we can give to $R(t)$ an intrinsic meaning complerly independant upon matter and its distribution. Now what sense do we make of $R(t)$ increasing? We can only make such senses if we have something to compare with.[12] In the cosmological game the independant yardstick is that of the frequency of light. The image is that of light being stretched

[10] Receeding velocities being proportional to the distance, this is nothing but the constant of proportionality, at the time of Weinbergs writing set at 15 km/s per 1 million lightyears

[11] This is a bit fanciful, as any counting presupposes that every element this is being counted is well-defined. But the principle is sound.

[12] One is reminded by the saying. *Today the universe became twice as big as yesterday, but no one noticed.* Yes why should anyone notice? Yardstick having become bigger as well.

out as space expands[13] which allows a different interpretation of the Doppler effect[14]. Now the very fact of introducing a global time parameter as all cosmologists do without blinking also seems to contradict the basic tenet of relativity theory that teaches us that there is no universal time, that the very notion of simultaneity is an illusion. Weinberg, perhaps wisely, refrains from commenting upon this. The point is that the notion of time is intimately connected with the way it is being measured. Clocks tick differently depending on the observer, and synchronization across space is hampered by the finite velocity of light setting the upper limit to the movement of physical bodies as well as information[15]. But if we think of space-time as an entity, we can contemplate its evolution, and this evolution is parametrized by some variable, which we may think of as universal time. In our particular example, the size of our common (common as it is intrinsic) yardstick $R(t)$ gives in fact a universal clock, the synchronization of which needs not to be effected as it is automatic. In fact the very fact that we can speak about the age of the universe, and thus its first three minutes of the title, presupposes this. Put in another way, the age of the universe is an invariant, supposedly independant of where we measure it[16]. If the universe would be truly static, then there would be no universal time. In other words the fact of a big bang, or more generally uniqueness of moments, effects a breaking down of symmetry.

The above has to be modified slightly. If we speak about the average distance between galaxies this does indeed depend on the observer exactly in the way proscribed by relativity theory. However given the fact of a homogenous distribution of galaxies, this breaks the symmetry of relativity theory. For an observer moving, say rapidly, the universe would no longer be isotropic, and he would notice a definite blue shift ahead of him, and would he care to turn his head around, an equally marked redshift. The sky would also be brighter in the direction of his travel than perpendicularly to it. He would also come up with a different average distance between galaxies[17]. His position would be an anamoly compared to us, because he is indeed moving with respect to the galaxies. The basic assumption of (special) relativity theory is that the laws of physics are the same in systems in uniform motion with respect to each other. Is the distribution of galaxies part of physics or just an accident? They are certainly not part of the 'axioms' of relativity theory. The Cosmological principle does not hold uniformly for all reference frames of uniform motion as we can speak of some of them (like ours) being in rest with respect to the distribution of (visible?) matter. When it comes to measuring the intrinsic lengths of space, I do not know

[13] As Hoyle noted, we could as well imagine the universe being fixed in size, and we humans and everything connected with us (like stars and galaxies) shrinking. Concluding that this is not as appealing to our egos.

[14] and one maybe to be treated a bit differently from the ordinary.

[15] We can of course set up virtual movements that travel faster than the speed of light. One obvious example is the Christmas tree twinkle. All over the night sky there are variable stars, we may think of succesive peaks of their luminosity to be formally linked to each other. This would lead to a virtual movement across the sky at a vastly superior speed

[16] This presupposes common intrinsic yardsticks, but the wavelengths of specified atoms, supply such.

[17] But if his velocity would be very close to light, he would indeed be travelling backwards in time, with respect to the galaxies he would catch up with. Howver, what sense would there be in the age of the universe to such a hurried observer.

the answer. As space is changing, its geometric nature only makes sense by fixing a parameter, namely that of formal universal time[18]. None of this is mentioned by Weinberg[19]. Wisely so. A writer of popular science needs to leave gaps (albeit fixable ones) as not to confuse his readers. Therein lies often as much expertise (if not much more) as that which is being actually displayed.

Now if we think of the galaxies as flying away from each other we can use some elementary Newtonian mechanics to both gauge the rate of increase of $R(t)$ as well as to postulate, depending on the amount of mass, whether the future of the universe will be one of endless expansion or whether it will come to a stop, i.e. $R(t)$ will reach its maximum, and then lead to a contraction. The analogy, mathematically exact in fact, is to a ball hurled away from the earth. If given enough velocity (escape velocity) it will never return. The calculation is elementary, to the effect of setting up the total energy of a galaxy with respect to an arbitrary ball of galaxies potential energy as well as its kinetic. This should be constant in time[20] which leads to $R(t)$ being proportional to $\sqrt{\rho(t)}$. If matter dominates $\rho(t)$ is proportional to $R(t)^{-3}$ and we thus concludes that $R(t)$ is proportional to $t^{2/3}$ and gives a condition in terms of the total mass of the universe and the Hubble constant[21]. Now both of those being notoriously difficult to estimate we cannot expect any definite prediction. The age of the universe on the other hand will only depend on the Hubble constant (which incidentally will be inversely proportional to the age of the universe as a very elementary calculation reveals) and is nowadays set at about 15 billion years [22]. The actual computations are usually never presented in any popular book on science, only at best the analogy above. Weinberg relegates it to a mathematical appendix.

Is the Universe finite or not. As was realised by the time of Newton, and known as the Olbers paradox, a homogenous distribution of stars in an Euclidean space (and also in fact in a Hyperbolic) would lead to the night sky being as bright as the surface of a typical star, in fact infinitely so. In the case of a finite (spherical) universe it would imply that the stars have only been shining for a limited time, otherwise the limited space would be overflowing with radiation. From the considerations above it appears that the universe is in fact finite, although it may of course expand without bounds, giving an illustration of the difference between actual infinity and potential. The critical mass value is often said to determine whether the universe is finite or not,

[18] Really a kind of meta-time

[19] Relativity theory is hard, in spite of the fact that it formally is so simple. One explanation could be that its contents are indelibly charged with meaning, and thus we entertain many preconceived ideas of what is true, unlike more formal mathematical deductive systems. Whenever something runs against intuition, you have to decide what basic dogma has to go. It is not always easy to know which dogma is more fundamental than the other. Thus mathematicians are not immune to make silly mistakes in relativity theory in spite of their ability to have a formal grasp.

[20] One may always add them all, or what amounts to the same thing, talk about the average

[21] If radiation dominates this has to be modified

[22] safely in excess of the 4.5 billion years of the earth based on totally different methods. Similar methods can also be used to give other minimum estimates based on the half-lives of isotopes. It is important to realise that all confirmations ultimately build on speculative chains of assumptions, so as noted above, confirmation really exists in that different approaches either lead to the same result, or at least not to conflicts.

it is not clear to what the word universe refers? The space-time continuum is an obvious choice, and thus one suspects that in the infinite case it should be a hyperbolic 4-manifold, barring local curvature irregularities, bound to be smoothed out. For presumably technical reasons popular accounts shy away from delving into this, and so does Weinberg.

Incidentally one may conceive of an infinite universe in which no point has a special position, avoiding the Olbers paradox. The principle is very simple and presented already by the Swedish cosmologist Charlier. A toy model on the real line explains it very well. Take a random sequence s_n of ± 1. Define the subsets U_n and the corresponding numbers m_n, r_n inductively as follows. $U_0 = \{0, 2\}, m_0 = r_0 = 1$ while $r_{n+1} = 3r_n, m_{n+1} = m_n + s_n m_n$ and $U_{n+1} = U_n \cup (U_n + s_n r_n)$. The 'universe' U is simply the union and consists of an infinite number of points ('stars') yet with no distinguished positions as the centers m_n have no limit. The density of stars go to zero as the radius r of the universe grows.

Weinberg spends little time on the geometrical aspects of cosmology, he is interested in the applications of particle physics. Basically he resorts to the stratification of temperature given by the threshold energies necessary for the production of various particles. Within different ranges he treats the universe as being in thermal stability. Thus the basic parameter is temperature not time, yet there is a simple relation, namely temperature is inversely proportional to scaling. The argument for this is simple. First energy of a radiating body is proportional to the fourth power of the temperature. Secondly as the universe expands the density of photons (as with matter) is inversely proportional to the cube of the scaling factor $R(t)$, but by the Doppler effect the wavelength is stretched by the same factor $R(t)$ and hence its energy is inversely proportional. This is of course nothing but the relationship that energy is proportional to frequency (the constant of proportionality being Plancks constant). Thus temperature is inversely proportional to $R(t)$. (But we have already seen that scaling is proportional to $t^{2/3}$ in the case of dominating matter, which incidentally, as this is the era in which most of the universe has existed, this gives us a clue as to the temperature of the background radiation, the fossilization of the radiation period, refering to estimates already given in the 40's.)[23]

The triumph of his calculations lies in predicting the present proportions of hydrogen and helium present in the universe (and hence the reason for his punchline in the original lecture). The point being that there is too much helium around as to be left from the buring of hydrogen fuel. There would be too many photons around otherwise and the sky would be too bright.

From this it is clear that a succinct and lucid presentation of the material would have been in the form of some clearly formulated assumptions and some simple mathematical manipulations[24]. But Weinberg has the ambition of writing to people who are not familiar (let alone comfortable) even with the exponential notation. Thus he prefers to write one hundred thousand million millions rather than 10^{11} (although the exponential notation is always supplied in parenthesis). In the same way rather than present a few simple formulas he couches the arguments in words. The professional needs to translate this back

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[23] As in the radiation case $\rho(t)$ is proportional to $R(t)^{-4}$ leading to $R(t)$ proportional to $t^{1/2}$ during this phase.

[24] Maybe in the form of exercises given to the reader with hints

into formulas to make sense of it; while one wonders at how much the non-professional can get out of it[25].

Such a approach would also highlight the strengths and weaknesses of the approach. It gives no illumination on the very early universe, as Weinberg acknowledges, as our understanding of particle interaction using the strong forces is poorly understood (or rather technically almost intractable[26]), More seriously one could imagine that as the temperature gets higher and higher new unpredictable laws of physics manifest themselves in an infinite process. The ultimate conviction of people in string theory is that this is not the case, that physics, and hence the real world, can be codified finitely. This if of course a metaphysical stand, and the point is not that this is not meant as a disqualification, only that ultimately you cannot avoid to make stands of that nature.

What to make out of all of this? Is it a swindle? After all our scientific conception of the universe has changed drastically in the last four hundred years, what guarantees are there that not a similar change will not effected in the next four hundred years, and that our descendants will laugh at the naivity of these calculations, in the same way we are amused by the crude attempts of the Vikings? Of course there are none, and this attitude is often taken by the clever and cynical ignoramus, from the sceptical peasant to the supercillious post-modernist. On the other hand such scepticism is based on a principle of time invariance, postulating that descendants will always repudiate their forefathers as a universal law (based on limited empirical evidence). Against this one may argue that science has a history, that at certain times it makes break-throughs and produce truths that essentially are permanent. The geometric insights of the ancient Greeks, albeit it of an elementary kind, have stood the test of time much better than their scientific. Ultimately of course things have to mesh with everything else, and have consequences, falsiable consequences. In a philosophical sense all knowledge is, as noted before, provisional, but this does not mean that it is arbitrary. No doubt the particulars of the story Weinberg presents have changed a lot in the thirty years that have gone by since he wrote the book, but the principles have not. The standard model remains the standard model even if it is modified here and there. And it will remain the standard model until if (if ever?) it will run into contradictions external as well as internal. And on yet a philosophical note the calculations are undertaken in the deep faith that mathematics means something, that it is not mere marks on paper signifying nothing. In fact at the very start of the universe all the major forces of nature were unified. As the temperature sank, symmetries were broken one after the other, and now they only exist in our mathematical calculations, the simplicity of which was then present not just as abstraction but concretely manifested. (The trouble was that there was no one there to observe them). What better illustration of the principle of the Pre-socratic philosopher Parmenedis does the really early universe

[25] Contrary to myth, the trouble to understand mathematics is not due its terminology, in fact the trouble is usually caused by the lack of its terminology.

[26] The author makes a reference to Feynman diagrams. In the case of weaker forces, the contribution of from each diagram quickly tapers off as they become more complicated, due to a convergence factor of $1/137$. In the case of strong forces the corresponding factor is much closer to one. In fact mathematicians suspect that the serieses diverge, but physicists are able to sum such anyway, much to the amazement as well as consternation of the more timid mathematicians.

presents when everything was one, and the confusing multifarious world of the senses was not. And also a declaration of faith in Platonism. Just as in the beginning of time forces were united, on a fundamental level religion and rationalism merge. Without some sort of faith no leap can be taken.

The more we understand the Universe, Weinberg notes, the more pointless it seems. Yet the efforts to understand it, he continues, raise us above the world of quotidian chores and elevate human life at least a little above that of farce and provide it with a modicum of the grace of tragedy.

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