An introduction to the accelerating universe

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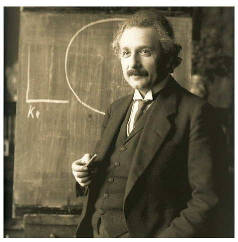
"You might expect gravity would slow it down,
but it's just expanding faster and faster."
Saul Perlmutter

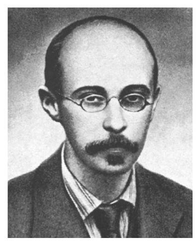
Modern cosmology is the fulfillment of the passion of humanity wondering through ages, about celestial objects brain teasing with their apparent movements in the sky. Cosmology, having evolved through ages, progressed at a rapid pace in recent times. Here we discuss the recent breakthrough, the discovery of acceleration of expansion of the universe which won the Nobel Prize in Physics for the year 2011. After Saul Perlmutter, Brian P. Schmidt and Adam G. Riess were honored thus for their seminal discovery, attempts on modeling of the cosmos followed. This article briefly describes the work along with the chief events in history which motivated the spectacular, fresh uprise of cosmology.

1 1915: Modern cosmology is born

The era of a series of sensational twists and turns in physics as it was, 20^{th} century began with breakthroughs in understanding of gravity and cosmology owing to Einstein, now renowned as father of modern theoretical cosmology, whereas Edwin Hubble, in the meanwhile, may be attributed to fathering the modern experimental cosmology. Einstein began a bold new era with space and time exposed as part-taking in the dynamics, rather than offering the ambiance as absolute entities, as assumed previously. The journey to the new order started in 1905, with the advent of his special relativity, as he announced having alleviated the conflict arised by Newtonian view of the universe. The new theory revealed space and time as mutually linked entities (not absolute and independent as in Newtonian dynamics). Any energy or momentum transfer phenomenon is constrained by the speed of light in vacuum as the limit, as the dynamics have space and time influence each other, to this effect. With this development, Einstein's mind had fresh conflicts too, with classical theory of gravity, as Newton's inverse square law assumed the phenomenon as force acting instantaneously, between two particles of matter separated by any distance, breaking the special relativistic speed barrier. An instantaneous action of force also violates relativity of simultaneity. Being dissatisfied, Einstein was on a lookout for an alternate theory on gravity. He labored with the tensor algebra and tensor calculus. This led to the path breaking discovery that gravity is the curvature of space-time in the presence of matter and electromagnetic field, rather than being a force. Einstein's Field Equation(EFE)s, as per the new theory of gravity, initiated the course of modern cosmology. This is attributed to gravity being the major controlling factor of the universe at large scales.



(a) Albert Einstein



(b) Alexander Friedmann

(c) Edwin Hubble

Figure 1: [Courtesy:Wikepedia and Pixabay].

1.1 Einstein's fresh worries

'Will the skies fall?' the cave man might have been worrying. Apparently, perhaps 50 millenniums after, Einstein worried almost the same way. The model of a universe with static space time was incomprehensible! The matter in the universe visible so far would have given way to enough gravity that it was time enough (as the picture was about an eternal universe) that the entire matter would have collapsed, dragging the space-time too alongwith them. A clueless Einstein introduced a term to his EFEs with a cosmological constant which was to generate an all pervading antigravity enough to balance the gravity. But it really opened up a fresh Pandora's box. Any slight disturbance, starting as a local effect would have grown over time into a total chaos, either leading to a big crunch, a gravitational collapse, or else it would have been a big rip, which would keep the space expanding, till ripping apart the very fundamental particles of matter and reducing electromagnetic radiation density to lifelessness.

1.2 Alexander Friedmann, Georges Lemaitre and Vesto Slipher

Alexander Friedmann's theoretical analysis accepted the assertion that universe viewed macroscopically, remains isotropic and homogeneous, where he agreed with Einstein endorsing the Copernicus view that humanity has no special significance in the universe. The Russian cosmologist's solutions for EFEs which showed non static, expanding universe a possibility, was very much the alleviation to the catastrophe with Einstein's static model. Friedmann further pioneered in, also to find out that EFEs admit universe expanding with acceleration. Georges Leimatre also arrived at non static universe models, independently.

The experimental cosmologist Vesto Slipher observed a large number of galaxies as exhibiting red shifts. But he had no way of measuring the distances to the galaxies, whereas E Hubble had, which made a big difference.

1.3 Hubble endorses Copernican view of the universe

Hubble, by 1929, became the first to measure distances to galaxies external to Milky Way, beyond its satellite galaxies LMC (Large Magellanic Clouds) and SMC(Small Magellanic Clouds). He was greatly equipped with the most advanced 2.5 m Hooker telescope, in Mount Wilson observatory with enough resolution to see bright individual stars in those galaxies. Again, it was two decades since Henrietta Levitt discovered the Cepheid variable stars as pulsating kind, had their period of luminosity cycle connected to their luminosities themselves and so realizing them as standard candles. A standard candle is a source of light with a known, fixed brightness by which the distance to it can be known by inverse square law of light. Hubble obtained first the distance to Andromeda and established it is another spiral galaxy like Milky Way, comparable by size, at a distance of about 20 to 25 times the diameter of Milky Way. Next he followed through to several number of galaxies of varying sizes, upto distances of about 30 Mpc. This established the 'island structure of stars,' with a humble note that ours is just one among numerously large number of galaxies(where stars remain concentrated, bound by their parent galaxy) around.

But the real wonder was yet in the waiting, as Hubble thus worked out distances to galaxies. He observed that galaxies were having redshifts proportional to their distances. The recession velocity for a star at a distance x was seen to be $v = Hx$, a relationship now renowned as Hubble's law (fig.2). H is a number, its recently obtained value being $\sim$70 km s^{-1} Mpc^{-1} (Mpc stands for the cosmology level length scale given by Mega parsec [1]).

However, it was observed that Andromeda galaxy is in a collision course with our galaxy as it is a blue shift observed with it. The observed blue shift (rather than a red shift) implies it is approaching with a velocity 110 km s^{-1}. So it is local movements dominating over cosmic recession motion for relatively small distances. At a distance 50 Mpc, the recession velocity turns out to be 3500 km s^{-1}, implying local movements becoming insignificant for larger distances. This explained why Slipher found a minority among the galaxies those are Milky Way's neighbors, not exhibiting red shifts.

[1] 1 Mega Parsec = a million parsec and one parsec $\sim$ 3.26 light years.

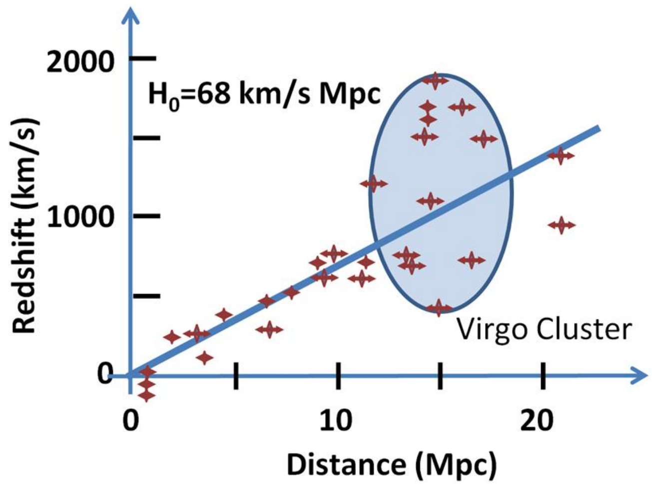


Figure 2: Hubble's Law:Data gathered on type Ia supernova by HST (Hubble Space Telescope) plotted. Can the deviation of data in Virgo cluster of galaxies be attributed to the local movements? Hint: The distance to center of the galaxy cluster is about 54 million light years. [Courtesy: NASA via Wikimedia Commons]

1.4 'My biggest blunder,' said Einstein.

What did it mean by galaxies apparently receding with recession velocities proportional to their distances and not by any of their own physical characteristics? It really meant a lot. It meant nothing short of space itself dynamic and expanding! Einstein, was more delighted that his dilemma ended; finally it was an apologetic Einstein acknowledging Friedmann was right and so also was Lemaitre. In case if expanding universe is assumed as the case of solution to EFEs, there are no worries about stabilizing a static universe, the delicacy behind which was so fine tuned between cosmological constant and the gravitating matter as to make it the most impractical model. Einstein openly admitted that his static model of cosmos was the 'biggest blunder'.

Thus, Hubble initiated experimental cosmology. Hubble, together with Einstein transformed cosmology into a science. The viewing of universe by large scale and its evolution, till then remained more of speculative kind, till this spectacular development.

1.5 Universe is simple enough, going by FLRW metric

It is a rare coincidence of luck that it was proposed and has been realized by now that the cosmos is isotropic and homogeneous when viewed macroscopically, accommodated in a flat 3D space. Alexander Friedmann, Georges Lemaitre, Howard P Robertson and Arthur G Walker had independently abstracted a model for cosmos accordingly and hence the name FLRW model. The universe being still 'more kind enough' to have a flat 3D space, makes matters greatly simplified that it has only much lesser number of terms in its metric for an elementary length dS, given by,

$$dS = \sqrt{c^2dt^2 - a^2(t)(dr^2 + r^2d\theta^2 + r^2\sin^2\theta d\phi^2)}. \tag{1}$$

$a = a(t)$ as a scalar quantity as a function of cosmic time alone, meets the requirement for homogeneity of space. Here the polar coordinates (with their usual mathematical description found in text books) are called 'comoving coordinates.' The space being flat, it also allows us to fix the point of time at which $a(t)$ can be $= 1$. So, it is customary to assume $a(t) = 1$ at present and this also means, for our universe expanding ever since big bang, $a(t) < 1$ in the past and it will be $a(t) > 1$ in future. The past behavior of the scale factor $a(t)$ is seen, as much as we receive light of the past from objects remote enough. Note that in this metric we have time also as an additional coordinate making a 4D space with our 3D space described by coordinates (r, θ and ϕ) remaining a 'hyper plane' in it.

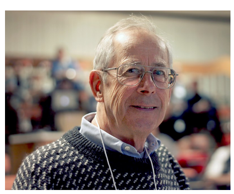
1.6 Friedmann Equations: Square of Hubble's constant is proportional to density of matter-energy content of the universe.

Friedmann equations are solutions obtained of EFEs in FLRW space with its metric given by eq.1. The homogeneity and isotropy inherent in the metric replaces whole of nerve racking, non linear EFEs, reducing them to an astoundingly simple equation. This equation turns out to be conceptually important too, as it brings out $H^2 \propto \rho$, where, $\rho =$ (sum over densities of components contributing to matter-energy to the universe[2]). That is, Friedmann equation brings yet another physics that the sum of densities of overall matter-energy content is directly proportional to square of Hubble's constant!! This straight away means the expansion of the universe is straight away linked to the sum of the densities of the components making the universe.

After some mathematical manipulations to Friedmann equations and using first law of thermodynamics (law of conservation of energy), we obtain another linearly independent equation that accommodates the acceleration

[2]Matter-energy contributing components are according to the model proposed for the cosmos and these can vary owing to exotic components proposed; for instance, the Lambda-CDM model has two exotic components namely dark matter and dark energy, Zel'dovich fluid is another exotic component in models making use of it.

of universe in it. The second equation incorporates a concept of pressure for individual components of the universe. This is understood because the macroscopic view of the universe has such vast empty space between particles of matter and dark matter[3](also note that the macroscopic view here is so huge that a particle in it contains billions of galaxies in it). Thus, universe at the macroscopic level is a fluid analogous to gas in a chamber with molecules as particles. Various constituents of the universe has pressures depending on their behavior at the macroscopic level. Einstein had a clever way of obtaining the pressure due to matter in the present universe as zero. During his time he assumed galaxies can be as good as particles. In kinetic theory of gas we know molecules as particles move randomly and this is what arises non zero pressure with gas in a container. However, galaxies as particles are not in random motion; rather they have local movements according to the gravity in their galaxy clusters. This means matter exert zero pressure. In the present universe this logic is extended to dark matter too, as the only interaction they are responsible for, as known, is via gravity. Besides, note that matter at ultra relativistic speeds (the case in which their kinetic energy remaining many times in excess of their energy equivalent of mass (by equation $E = mc^2$)) and electromagnetic radiation exert pressure, proportional to their total energy (approximately equal to kinetic energy in the case of ultra relativistic matter) . Yet again, matter had ultra relativistic energy only in a very little fraction of a second after Big bang. The pressure of contents of the universe played a major factor in the evolution of the universe; various roles at various times. The dark energy, another exotic component we are going to discuss here exerts negative pressure which favors acceleration to expansion of the universe.



(a) James Peebles

(b) S Perlmutter, A Riess and B Schmidt

Figure 3: [Courtesy:Wikepedia and Pixabay].

[3]Universe viewed macroscopically has matter and dark matter taken together having a density $\sim 6 \times 10^{-27}$ kg m^{-3}, same as the average density of a cube of 3 m side containing 6 Hydrogen atoms. Hydrogen gas maintained under NTP will have about 7×10^{26} atoms in the same space!!

2 The Accelerating Universe

By solving the Friedmann's equation, together with the equation of acceleration mentioned above, we obtain an expression for H, the Hubble's constant, in terms of a and hence cosmic red shift z of the the object, using $a = \frac{1}{1+z}$. Note that the word 'constant' in the name 'Hubble's constant' is a misnomer as of now, as H is no more a constant, but a time dependent parameter, decaying with the density of mass-energy content in the universe, starting from infinity at the time of Big Bang. An integral equation connecting H with z (derived by manipulating Friedmann equation and the equation of acceleration), obtains its theoretically estimated distance at the time it emitted the light which is received by now, as per the theoretical model of the universe. When this is estimated with the standard candle that is type Ia supernova, we will be able to compare its value with its distance experimentally obtained by measuring its apparent brightness.

2.1 Type Ia supernova as standard candle:

Type Ia supernova(see fig4), owing to its way of creation, is more precise a standard candle than Cepheid variable. With most powerful telescopes, a Cepheid variable can be seen from a maximum distance of 100 million

Figure 4: HST image of Type Ia Supernova 1994D, with its host galaxy NGC 4526 in the background. At z$\sim$0.0015, it is at a distance d$\sim$55 million light years from Earth. Note that its phenomenal brightness makes it seen as distinct enough, even as the other stars in billions, appear together like fog [Courtesy: NASA]

light years whereas the brightness of type Ia supernova being 5 billion times that of a Sun like average star, can be seen from a distance of about 8 billion light years. This means we can look deeper into the past of the universe.

Perlmutter as a member of Supernova Cosmology Project, Schmidt and Riess as members of High-Z Supernova Search Team wanted to measure what they anticipated as the deceleration of expansion of universe. The anticipation of deceleration was natural, as they knew the universe had visible matter and exotic dark matter 6 to 7 times as the former mentioned component by mass, generating the gravity for slowing down the expansion. However, independent as their data collection and speculations as they were, the common result they arrived at was a stark contrast to their expectation. They found the expansion of the universe is accelerating, rather than decelerating. The advanced experimental research works on CMBR (Cosmic Microwave Background Radiation, the process in which the universe has a holistic background radiation following Big Bang) and BAO (Baryon Acoustic Oscillation, basically the giant acoustic ripples with galaxies themselves as points in it, owing to what followed as violence succeeding the sudden escape of electromagnetic radiation, about a few lakh years after Big Bang, when the size of the universe was large enough to have baryonic matter (whole of visible matter, previously preventing photons from escaping) rarified enough) signatures, using BOOMERanG (International project using high altitude balloons , 1997 to 2003) project, COBE (NASA space craft, 1989 to 1993), WMAP(NASA spacecraft, 2001 to 2012) and Planck(ESA spacecraft 2009-2013).

2.2 Modelling the accelerating universe

The data confirmed the fact that the expension of universe initially decelerated and progressively switched over to acceleration about 7 billion years ago, roughly at a time 50% of the age of the universe was reached. Ever since, as per the data, the expansion of the universe is progressively diverging to higher acceleration, predicting a Big Rip, in a remote future.

The Friedmann equation and equation of acceleration helps fit the right model by theoretically calculating the distance to a type Ia supernovae observed at a given z. The theoretical distance is expected to match the experimentally obtained distance from its apparent magnitude, for being a standard candle.

2.3 Lambda-CDM model

So far it is Lambda-CDM model that remains the best fit. The success of this model in explaining the type Ia supernovae data is highly endorsed by its success in explaining a great deal of other empirical data, those of BAO, abundance of light elements in the universe and formation of large structures of galactic super clusters. Another remarkable success with the model is that it remarkably well fits the estimated age of the universe, obtained from globular clusters data. As indicated by the chart in fig.5, the dark energy has a constant value for density, with its total contribution to mass-energy content increasing over time. Each of the other components keep their total mass-energy as constants, with their densities decreasing over time. Dark energy is

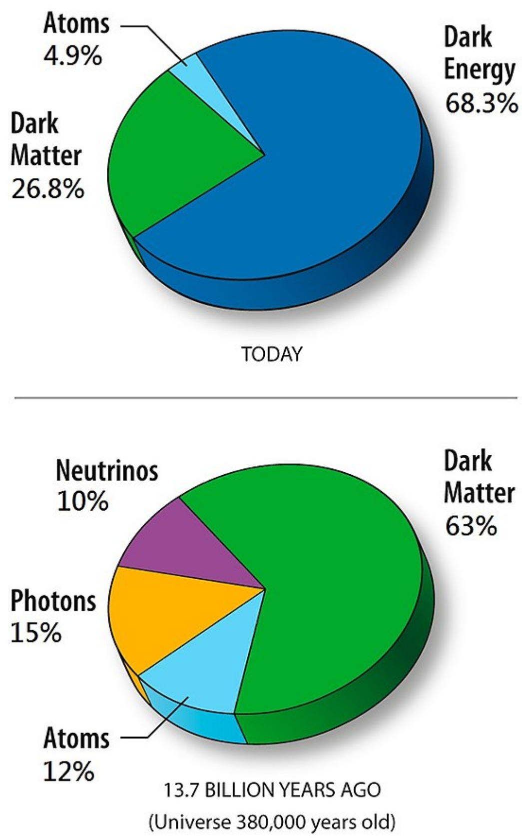


Figure 5: Chart on constituents in Lambda-CDM model of the universe, as per their share of total mass energy as on today and just after Big Bang. All the constituents, had played their roles at different stages of the evolution of the universe. [Courtesy: Wikiwand, originally as per Planck(ESA space craft) data]

the all pervading component, now having the lion's share of 68% of the overall mass-energy as on today. In the beginning, as in the chart, dark energy had an insignificant role in the universe dynamics. As the only component responsible for negative pressure, imparting acceleration to the expansion of the universe, dark energy matched its role with that of matter in the dynamics of the universe about 7 billion years before, as per the Lambda-CDM model. That was the point of cosmic time from where the acceleration started for the expanding universe. Previous to this, it was a matter(to the macroscopic cosmos scale, it is dark matter that plays a significant role in this phase) dominating era ever since 47000 years after the Big Bang, a period of deceleration. It is at this point one comes to doubt how far the speculations are true. However, Jim Peebles, another Nobel laureate cosmologist of this century, had built up a sturdy frame for physical cosmology by rigorous analysis of data of fluctuation pattern gathered by Planck space craft on CMBR. He could mathematically predict the role of dark matter in formation of large structures, exactly tracing as they occur. His proficiency in the field also accounted the role of dark energy too.

2.4 Challenges for the Lambda-CDM model

Despite the phenomenal success of Lambda-CDM model, quite outsmarting other proposed models, at present it faces problems, the gravest two of them being:

2.4.1 Cosmological fine tuning problem

The over all density of mass-energy content in the universe differs between the predictions by Lambda-CDM model and that by the theoretical prediction due to quantum field theory by what is called sum over zero pont energy states in vacuum. And how much? The ratio of the predicted values by the former mentioned theory and that by the latter mentioned is by a whopping 10^{-121}. This is so far the biggest ever catastrophy in terms of conflicts between two theories, each of them known for explaining a wide range of empirical facts.

2.4.2 Cosmological coincidence problem

With the Lambda CDM model, we find that one major contributing component namely the dark energy keeping a constant value of density throughout the evolution of the universe, has same order of magnitude of density as that of the other dominating component, dark matter, at present. This situation is crucial enough that otherwise, the universe would not have been in the current form as it is today, for supporting the existence of life and humanity in it. This situation to occur, requires such initial conditions in the initial stages of the evolution of the universe, far less probable than perhaps obtaining one lakh consecutive head events with a coin tossed for equal number of trials.

2.5 A few alternate models for late accelerating universe:

There are wide spread attempts for alternate models to alleviate the mentioned short comings. A few of them to name are Quintessence field, K-essence field, Phantom field, Tachyon Field Theory (care should be taken that this is a misnomer - it has nothing to do with the hypothetical particles called tachyons proposed to move faster than light), Chaplygin gas, f(T) models, Holographic dark Energy, Bulkviscous CDM models and Bulk viscous Zeldovich fluid models.

Overall, the discovery of acceleration of the universe and thereby a fresh Lambda-CDM model for cosmos as most successful alongwith its shortcomings, reminds one of Bernard Shaw cutting a joke during a felicitation of Albert Einstein, ‘Newton made a universe which lasted 300 years. Einstein has made a universe, which I suppose you want me to say will never stop, but I don’t know how long it will last.’

(The author Dr. K Rajagopalan Nair is an active researcher and teacher of physics. He has a Ph.D in Physics in the area of cosmology from CUSAT (Cochin University of Science and Technology), India. He was a faculty member in the department of physics at the National Defence Academy. He has also done research in University of Pune, and the National Chemical Laboratory, Pune).