International Journal of Scientific & Technical Development
(A Peer-Reviewed Bi-Annual Journal) ISSN: 2348-4047

Exploring the Enigmatic Components of the Universe

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Abstract
A number of cosmological observations over the last decades have provided us compelling evidence that the ordinary hadronic matter constitutes only around 5 percent of the Universe. Rest 95% can be attributed to the two unknown forms of energy, viz. the Dark Matter and Dark Energy. Formulating a successful theory for the composition of these mysterious constituents as well as experimental detection of the proposed constituent particles continues to be one of the most outstanding problems in the present day high energy physics. In the present article, beginning with the experimental evidence for the existence of dark matter and dark energy, a brief overview of various theoretical speculations for their composition would be provided. Further, experimental status of some of the ongoing and future searches for dark matter and dark energy components would also be briefly discussed.
Keywords:Dark matter, dark energy, LHC, direct searches, WMAP.

1. INTRODUCTION

Ever since the dawn of civilization, man has been fascinated by the stars, planets and other "heavenly" objects, wondering what essentially the magnificent universe around us is made up of. More than eighty years ago, Edwin Hubble established the expansion of the universe with his pioneering observations of galaxies. Since then, galaxies have been the fundamental tools for understanding the structure and evolution of our universe. After decades of exhaustive and increasingly precise astrophysical observations, scientists today have evidence that what we have always thought of as the actual universe- the planets, stars, galaxies, all the matter in space- represents less than even a mere 5 percent of what's actually out there. The rest is something they call as 'dark matter' (23 percent) and approximately 73 percent is something even more mysterious, which they call as 'dark energy'. The present article aims to introduce the reader to the enigmatic concepts of dark matter and dark energy along with shedding some light on the exciting questions such as why do we need dark matter, what is it believed to be consisting of etc..

Let us first begin with by formally introducing both of these. Dark matter is a term used to describe matter that can be inferred to exist from its gravitational effects, but does not emit or absorb detectable amounts of light. On the other hand, the term 'dark energy' although seems to be linked to dark matter through the mass energy equivalence, is actually a counter force. A formal definition of the term 'dark energy'can be given as-
a hypothetical form of energy that permeates all space and exerts a negative pressure, so as the universe expands, the pressure increases and causes the universe to expand at an ever-increasing rate.

We would like to narrate the story of dark matter and dark energy intwo parts. Firstly, we would discuss the experimental signals as a consequence of which we believe that these exist. Secondly, we would discuss some of the possibleexplanations as to what both of these mysterious entities are made up of.

2. MOTIVATION FOR DARK MATTER

We call something dark because it (almost) neither emits nor absorbs electromagnetic radiations. Historically the observational evidence for the existence of dark matter came from analyses of galactic dynamics and cosmic microwave radiation. The following discussions in this section show that the observed luminous objects can not have enough mass to support the observed gravitational effects.

- Galactic Rotation Curves:It was Swiss astronomer Fritz Zwicky in 1933 who, while studying clusters of galaxies, found that the mass in the galactic plane must be more than the material that could be seen. By applying Virial Theorem, i.e. the total kinetic energy should be the half of the total gravitational energy, Zwicky estimated the total mass of the cluster based on the motion of galaxies near its edge and compared it to the one based on the number of galaxies and total brightness of the cluster. He found that there was about four hundred times more estimated mass than was visually observable. Further evidence for dark matter came from the measurements of rotations of spiral galaxies in 1950's and 1960's. By the virtue of virial theorem, astronomers expected the stars near the center of a galaxy, where the visible mass is concentrated, to move faster than the stars at the edge. However, what they actually observed was that the stars at the edge of the galaxy had nearly the same rotational velocity as the stars near the center. Both these observations implied that the galaxies and galactic clusters must contain an 'invisible' form of matter - "dark matter"- in a proportion substantially larger than the usual 'visible' matter, responsible for the observed gravitational effects. As astronomers focused their attention to dark matter, they began to collect additional evidence for its existence.

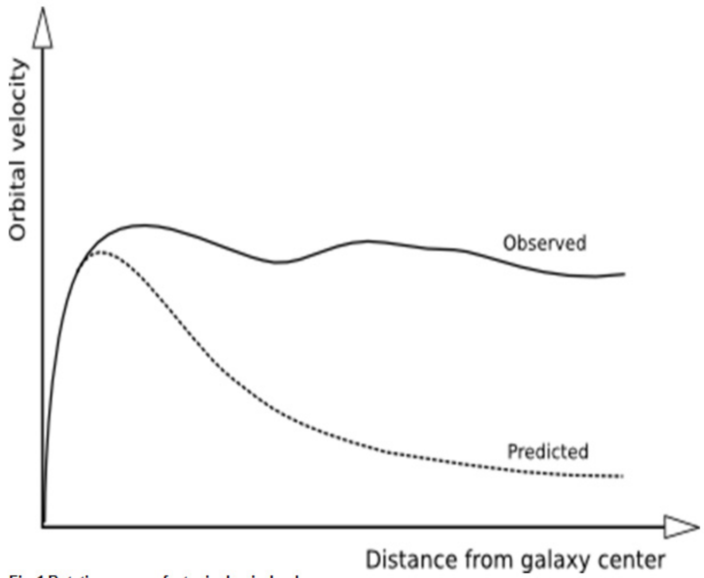

Fig.1 Rotation curve of a typical spiral galaxy

Fig.1 Rotation curve of a typical spiral galaxy

- Confinement of hot gas in the galaxies: Expecting to find pools of hot gas, which had previously gone undetected and which might account for the mass being attributed to the dark matter, some of the astronomers turned their attention to galactic clusters. The basic technique was to estimate the temperature and density of the gas from the energy and flux of the X rays using X ray telescopes, which would further enable the mass of the galactic cluster to be derived. The measurements of hot gas pressure in galactic clusters by X ray telescopes, such as Chandra X Ray Observatory by NASA, have shown that the amount of superheated gas is not enough to account for the discrepancies in mass and that the visible matter approximately constitutes only 12-15 percent of the mass of the cluster. Otherwise, there won't be sufficient gravity in the cluster to prevent the hot gas from escaping.
- Gravitational lensing: It has been shown that the clusters and superclusters can distort space-time with their immense masses. Light rays emanating from a distant object behind a cluster pass through the distorted space-time, which causes the rays to bend and converge as they move towards an observer. Therefore, the cluster acts like a large gravitational lens. By measuring the angle of bending, the mass of the gravitational lens can be calculated - the greater the bend, the more massive the lens. Using this method, astronomers have confirmed that the galactic clusters indeed have high masses exceeding those measured by the luminous matter, thereby providing additional evidence for the existence of dark matter.
- Fluctuations in Cosmic Microwave Background Radiation: Cosmic Microwave Background Radiation (CMBR) can be considered as the radiation left over from an early stage in the development of universe. The analysis of CMBR reveals what the universe was like when it was only a few hundred thousands years old, long before galaxies and the clusters of galaxies were formed. The intensity of CMBR is very nearly the same in all directions however small variations of a fraction of a percent have been detected. These fluctuations (anisotropies) are due to clumps of matter that were either hotter or cooler than the average, representing the seeds of all future structures - the stars and galaxies of today. The rate at which these clumps would grow in a hot, expanding gas can be calculated from different admixtures of the normal visible matter, photons, protons, neutrons etc., and dark matter. Comparison of such calculations with the observations of CMBR by Planck mission team in 2013 have shown that the total mass energy of the known universe contains 4.9 percent ordinary matter, 26.8 percent dark matter and 68.3 percent dark energy. Thus, dark matter is estimated to constitute 84.5 percent of the total matter content in the universe, while dark matter plus dark energy constitute 95.1 percent of the total matter energy content of the universe.

3. EVIDENCE FOR DARK ENERGY IN UNIVERSE

In 1929, the astronomer Edwin Hubble had discovered that distant galaxies were moving away from us and the farther away they got, the faster they seem to be receding. This was a revolutionary idea which showed that the universe, which was once supposed to be stationary, is actually alive in time, like a movie. Rewinding the film of expansion, the universe would eventually reach a state of infinite density and energy - “The Big-Bang”. But the more perturbing question is - how would it end, what is the probable fate of the universe. The universe is full of matter and matter attracts other matter through gravity. Astronomers reasoned that the mutual attraction among all the matter may be slowing down the expansion of the universe. But what would be the ultimate outcome –

• Would the gravitational effect be so forceful that the universe would actually stretch a certain distance, stop and then reverse itself, like a ball tossed in air?
• Would the effect of gravity would be so slight that the universe would escape its grasp and never stop expanding, like a rocket leaving earth’s atmosphere?
• Would the gravity ensure a rate of expansion neither too fast nor too slow, so that the universe would eventually come to a virtual standstill?

With an aim to measure the rate of expansion of the universe, two teams, one led by Saul Perlmutter at Lawrence Berkeley National Laboratory and the other by Brian Schmidt at Australian National University, closely analyzed a number of supernovas throughout the 1990’s. In 1998, both the teams reported their observations whichsurprised the scientific community. They found that the light from the distant supernovas is inexplicably faint. The best explanation for this is that they are more distant than originally thought, which implies that the expansion of the universe is not slowing down, as expected, but accelerating. This discovery implied that the dominant force in the universe is not gravity, but something else. It was Michael Turner, a cosmologist at the University of Chicago, who coined the term Dark Energy for this “something”.Dark energy is a thus a kind of repulsive gravity, actually pushing the universe apart. The effect of dark energy is small for objects of the size of galaxies and stars, but is critical for understanding the large-scale structure of the universe. Saul Perlmutter, Brian Schmidt along with Adam G. Riess, an American astrophysicist, bagged the 2011 Nobel Prize in Physics for this discovery of accelerating expansion of universe.Aseries of supernova surveys in the past decade have measured hundreds of distant supernovae and greatly strengthened the case for cosmic acceleration and by implication, dark energy.

Apart from the Supernovae, there are many other cosmological observations which stand in need of dark energy for their explanation, some of which are briefly discussed below.

• **X-ray emission from clusters of galaxies:**

The study of X-ray emission from clusters of galaxies has been proven to be a powerful technique for gathering evidence for the existence of dark energy. Broadly, it proceeds along two lines of approach. One method, called the “growth of structure” method, relies on observing how the number of galactic clusters changes with time. Data collected by NASA’s Chandra X-ray observatory provides high quality estimates of cluster mass as a function of time which can then be compared with predictions from models of the expansion of the universe with and without dark energy. The results are in good agreement with the conclusions from the supernova data. Another approach uses Chandra data to determine the ratio of hot gas to dark matter in clusters. Computer simulations for clusters indicate that this ratio should be nearly constant with time. The only model for the expanding universe that reproduces this result is the one that contains dark energy in an amount consistent with the estimates from supernova studies.

• Cosmic microwave background radiation and largescale structure: Tiny temperature variations or fluctuations (at the part per million level) in the Cosmic microwave background radiation (CMBR) have been detected with the NASA’s Wilkinson Microwave Anisotropy Probe (WMAP) and other telescopes. Highly accurate measurements of the fluctuations by WMAP indicate that the amount of dark energy required is consistent with the results of supernova and cluster studies. Observations of the CMBR by the Planck spacecraft have recently given a more accurate estimate of the composition of the universe - 68.3 percent of dark energy, 26.8 percent of dark matter and 4.9 percent of ordinary matter. This pattern remains imprinted on the distribution of matter, and shows up in the distribution of galaxies formed hundreds of millions of years later. The theory of large-scale structure, which governs the formation of structures in the universe (stars, quasars, galaxies and galaxy groups and clusters), also suggests that the density of matter in the universe is only 30 percent of the critical density, supplying yet another evidence for the existence of dark energy.

4. OUR UNDERSTANDING OF DARK MATTER AND DARK ENERGY COMPOSITION

Discussion in the previous sections clearly brings about the fact that a major chunk of our Universe is made up of these mysterious forms, viz. Dark matter and Dark energy. In this section, we would briefly discuss ourunderstanding of the what these two can be made up of.

4.1 DARK MATTER

Some astronomers believed that the missing matter could simply be made up of the regular baryonic matter (the protons and neutrons), however more difficult to detect. Such dark matter candidates are referred to as Massive Compact Halo Objects (MACHOs), which are believed to be large objects residing in the halos of galaxies, but eluding detection because they have very low luminosities. Such objects include brown dwarfs, white dwarfs, neutron stars and even black holes. However, the theory of Big - Bang Nucleosynthesis as well as the experimental evidence from anisotropies in CMBR observed by NASA's Wilkinson Microwave Anisotropy Probe (WMAP) and Planck mission team have produced an upper bound (5 percent) on the total amount of baryonic matter in the universe. So far, we have probably contributed somewhat to the dark matter mystery, but there are not simply enough of them to account for all the dark matter in the universe, most of the dark matter is thus attributed by the non-baryonic stuff.

The non-baryonic dark matter candidates can broadly be grouped into two categories-

- Hot Dark Matter (HDM)
- Cold Dark Matter (CDM)

depending upon their respective masses and speeds. CDM is composed of substantially massive particles expected to be moving at sub relativistic speeds, whereas HDM consists of particles with zero or nearly zero mass which are expected to be moving nearly at the speed of light, when the pre-galactic clumps began to form. This classification has observational consequences for the size of clumps that can collapse in the expanding universe. HDM particles are expected to be moving so rapidly that clumps with mass of the order of that of a galaxy would quickly disperse. Only clouds with the mass of the order of thousands of galaxies, i.e., the size of galaxy clusters, can form. Individual galaxies could have been formed later as the large cluster size clouds fragmented, in a top-down process. In contrast, CDM can form clumps of mass of the order of that of a galaxy or less. Galaxies would be formed first and clusters would be formed later as the galaxies merge into groups and groups into clusters in a bottom-up process. HDM may include (massive) neutrinos, but the top-down formation scenario for galaxies has largely been ruled out by the observations of high red shift galaxies such as Hubble Ultradeep field. The observations with Chandra also show many examples of clusters being constructed by the merger of groups and sub clusters of galaxies. This and the other line of evidence that galaxies are older than the groups and clusters of galaxies strongly support the CDM alternative.

The leading candidates for CDM are particles called WIMPs (Weakly Interacting Massive Particles). WIMPs could include large number of exotic particles, such as,

• Neutralinos- Hypothetical particles that are similar to the neutrinos but are heavier and slower. In many models of beyond standard model particle physics, e.g. in the MSSM (the minimal supersymmetric standard model), the lightest supersymmetric particle is generally thought to be the lightest neutralino. Although neutralinos have not been discovered yet, they are a front runner in the WIMPs category.

• Axions- Neutral particles with mass less than a millionth of that of an electron. Axions have a specific type of self-interaction that makes them a suitable CDM candidate. Axions have a theoretical advantage that they solve the Strong CP Problem in Quantum Chromodynamics, but have not been detected yet.

• Photinos- Fermionic partner of photon, similar to photons but with spin 1/2, each with a mass ten to hundred times that of a proton, predicted by supersymmetry. Photinos are uncharged and, true to the WIMP signature, interact weakly with matter.

Till date, the experiments at the Large Hadron Collider (LHC) have failed to find any evidence for the existence of photino. Other possibilities that have been discussed in literature include sterile neutrinos and Kaluza-Klein excitations related to the extra dimensions in the universe.

4.2 DARK ENERGY

Comparison of the age of the universe deduced from the expansion rate of the universe with independent age estimates also provides an important check on the amount of dark energy driving the acceleration of the expansion. The ages of the oldest known stars constrain the age of the universe to be in the range 12 to 15 billion years, which is again consistent with estimates of the amount of dark matter and dark energy.

Apart from the above, the gravitational lensing technique (as discussed in the case of dark matter), based on bending of light from a background object due to the presence of galaxies and clusters of galaxies, also provides evidence for the presence of dark energy with an amount consistent with the other cosmological observations.

From the above discussion, it is apparent that the observational evidence for the existence of dark energy is extremely compelling. However, understanding the origin of this acceleration is one of the greatest unsolved problems in contemporary science. Explanations for the presence of dark energy can broadly be categorized into three approaches

- Vacuum energy: The most straightforward explanation for dark energy is that it is a property of space. Albert Einstein was the first person to realize that the empty space has some amazing properties, e.g. it possesses its own energy - the "vacuum energy". Mathematically, it is equivalent to the addition of a constant term, the 'Cosmological Constant', in the equation that describes the expansion of the universe. Essentially, the cosmological constant corresponds to the value of the energy density of the vacuum of space, originally introduced by Einstein in 1917 to achieve a static universe, then dropped after Hubble's 1929 discovery that the universe is expanding. From 1929 until the early 1990's, when the presence of dark energy was experimentally confirmed, most of the cosmologists assumed the cosmological constant to be zero. While dark energy is poorly understood at a fundamental level, its main required properties are that it dilutes much more slowly than matter as the universe expands, and that it clusters much more weakly than matter, or not at all. The cosmological constant is the simplest possible form of dark energy since it is constant in both space and time. So far, various probes of dark energy are consistent with a constant value for the vacuum energy. With the development of quantum mechanics, attempts to deploy it for the explanation of the origin of vacuum energy commenced. It was realized that "empty space" is actually full of virtual particles which continually form and then disappear for extremely short time intervals. The effects of these "virtual particles" have been measured in the shift of energy level of hydrogen atoms and in particle masses. However, attempts to estimate the energy density associated with the quantum vacuum lead to an extremely absurd result that the amount of vacuum energy density should be approximately 1020 times more than observed. No satisfactory explanation for resolving this enormous discrepancy has been put forward till date. Thus, the physical basis for vacuum energy continues to be a complete mystery as yet. Advances in understanding the nature of elementary particles, perhaps simulated with the discoveries by LHC at CERN, may shed light on the vacuum energy in near future.
- Quintessence: Vacuum energy, or the cosmological constant is, as the name implies, constant in space and time. A more general approach assumes that the vacuum energy can vary over space and time due to the existence of a new force field which is called a scalar field, or quintessence. It is expected that this scalar field would affect the expansion of the universe in a manner opposite to that of matter and normal energy. This, however, gives rise to an interesting question - "why the cosmic acceleration began when it did". If cosmic acceleration began earlier in the universe, structures such as galaxies would never have had time to form and life, at least as we know it, would never have had a chance to exist. Many models of quintessence have a so called "tracker behaviour", which solves this problem. Such models assume that the scalar field energy density tracks (but is less than) the energy density of radiation and matter at very early times and then comes to dominate the energy density of the universe at later times. Many versions of scalar fields have been proposed, but as yet none has emerged as a favorite. Experimentally, no evidence of quintessence is yet available, but it has not been ruled out either. An important goal of future research is to distinguish between vacuum energy and scalar fields as dark energy candidates. The most promising way is to use different experimental methods described above to determine the exact relation between the density and pressure of the dark energy. This relationship is expressed as pressure = (w) × (density), where w is called the "equation of state parameter". For vacuum energy, the value of w is equal to -1, whereas for scalar fields, w can be less than or greater than -1, and it can vary with time. To date, all observations are consistent with w = -1, but other values, as well as variation with time, are also possible.
- Neutrino dark energy: In the past few years, numerous attempts have been made to study the possible connections between the neutrinos and the dark energy. There are at least two observations which motivate these studies: • The dark energy scale 10−3 eV is smaller than the energy scales in particle physics, but interestingly is comparable to the neutrino masses.
- In Quintessence-like models of dark energy, mass of the scalar field, mQ is approximately 10−33 eV, which surprisingly is also connected to the neutrino masses via a seesaw formula

mQ m2ν / MPl,

with MPl ≈ 1019 GeV being the planck mass, the scale for quantum gravity.

On the basis of the arguments given above, it is quite interesting to make a speculation regarding the connection between the dark energy and neutrinos. If such connection exists in nature, then in terms of the language of the particle physics it requires the existence of new dynamics and new interactions between the neutrinos and the dark energy sector. Qualitatively these models have made an interestingprediction, viz., neutrino masses are not constant, but vary during the evolution of the universe. The predictions on the variation of the neutrino masses can be tested with Short Gamma Ray Burst, CMB and much more interestingly and importantly in the experiments of neutrino oscillations. If the interactions between dark energy and the neutrinos indeed exist, they will open up some possibilities of detecting the dark energy non-gravitationally. Recently, some interacting dark energy models, where the dark energy sector is closely connected to the Higgs and the Top quark in the standard model of elementaryparticlephysics(SM), have also been proposed in literature. One has to wait for future experiments to learn more about the dark energy and hence confirm or rule out these models.

5. ARE DARK MATTER AND DARK ENERGY RELATED?

It is natural to conjecture the dark matter and dark energy as two different manifestations of the same physical quantity in view of the Einstein's famous mass-energy equivalence relationship. However, it needs to be emphasized here that as per the present cosmological evidence, the two do not seem to berelated to each other. Dark energy is the force responsible for the acceleration of the expansion of the universe at an everincreasing rate since the Big Bang. Dark matter, on the other hand, is the force that keep the universe together and explains how the cohesion of the stars, galaxies and even the galactic clusters is possible. The influence of dark energy is largely repulsive, whereas that of dark matter is attractive. Thus, dark matter and dark energy appear to be competing forces in our universe. The only thing they have in common is that both were forged in the 'Big-Bang' and both remain mysterious.

6. CONCLUSIONS

In conclusion, we would like to state that understanding the dark matter and dark energy is one of the biggest challenges to the presentday particle physics. Dark Matter is a mysterious form of matter which has been proven to constitute around 26% of the total mass energy of the Universe. As per our present knowledge, it is largely supposed to be consisting of non baryonic components-viz. WIMPs.

On the other hand, dark energy is even more mysterious and is related to the wellestablished phenomenon of acceleration of the expansion of the universe.At present, the simplest possible explanation, vacuum energy, is consistent with all existing data, but the theory provides no understanding of why it should have the requisite small value. An impressive array of experiments aiming to understand the origin of dark energy are underway or are planned, hoping to make a significant progress in the next fifteen years.

In conclusion, we would like to state that powered by robust instruments, bold ideas and profound mysteries, we are certainly in a revolutionary era of discovery to understand the universe and our place in it.We have to wait for more data to arrive at a conclusive theory of these mysterious constituents of Universe.

ACKNOWLEDGEMENTS

The author would like to thank the Principal, Goswami Ganesh Dutta Sanatan Dharma College, Chandigarh for providing the necessary facilities to work.

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