Cosmology Essay: A review of Dark Matter and Dark Energy

Howard Kinsman

May 4, 2017

1 Introduction

Many observations and theories of the universe have found that approximately 95% of the mass and energy in the universe is dark and invisible, the true nature of which is largely unknown. The matter component is known as dark matter (DM) and the energy component dark energy (DE) This is a brief review of the history and current status of DM and DE.

2 Dark Matter

DM has a surprisingly long and interesting history. In 1937 Fritz Zwicky published a paper on the velocity dispersion of galaxies within the Coma cluster. He found that the velocity dispersion of galaxies within the cluster was so high that in order for the system to remain stable there must be some "missing mass" i.e. mass which is not detectable optically. Further research in this area continued but it wasn't until the 1970s when astronomers began accurately measuring the rotation curves of spiral galaxies, with the discovery of H1 21cm radio emission, that interest in this area became of great importance. Rotation curves are a measure of the orbital velocity of the stars and gas in a galaxy plotted as a function of distance from the galactic centre. According to Keplerian laws rotation curves would be expected to decline with increasing radius however it was found that they remain flat i.e. constant, all the way out to the largest radii observed, both optically and with 21 cm. According to Newtonian gravity this implies that there must be some "hidden mass" within the galaxies exerting a gravitational effect on the system resulting in these flat rotation curves. This "hidden mass" was termed dark matter.

Apart from high velocity dispersions in galaxy clusters and flat rotation curves other evidence for DM includes gravitational lensing, hot gas in clusters, the Cosmic Microwave Background (CMB) and through computer modelling of the growth of large scale structure in the early universe (discussed later). Gravitational lensing occurs when light from distant galaxies behind a galaxy cluster is distorted due to the large gravitational pull of the cluster. This is known as strong lensing and is quite rare, however weak lensing also occurs where there is just a small distortion of the galaxies size and shape. The mass of the galaxy cluster can be measured and compared to how much the light is expected to be bent by gravity. The results show that there must be far more mass in the cluster than can be detected. Galaxy clusters when viewed in X-ray reveal huge amounts of hot gas which can be explained by large amounts of DM which provide a potential well to hold the gas. The CMB is the remnants of radiation from the early universe. Anisotropies in the CMB reveal evidence for DM. Before decoupling from baryonic matter (i.e. protons and neutrons), photons underwent oscillations that froze in at redshift $z \approx 1100$. By studying the height of the peaks in these oscillations it has been found that the universe is comprised of approximately 5% baryonic matter, 26% dark matter and the remainder dark energy (discussed later). Some authors (Freese, 2017) regard the evidence of DM from the CMB as "irrefutable".

Further evidence of DM, which has been described as "direct empirical proof" (Clowe et al, 2006), has been found in observations of the Bullet cluster of galaxies. The Chandra X-ray observatory has detected the baryonic matter in the merger of two smaller clusters, whilst DM has been deduced from gravitational lensing, and they clearly show that are behaving differently. At the collision point the baryonic matter has slowed down due to friction whilst the DM has passed through this point.

With the growing evidence for the existence of DM, obvious questions to ask are "What is it made of?" and "Is it baryonic?". About twenty years ago it was suggested that dark matter is comprised of objects such as faint stars, sub-stellar objects or stellar remnants. Collectively these came to be known as massive compact halo objects (MACHOs). However recent studies (Freese, 2017) have found that these objects couldn't account for all the DM in the universe. This then suggests that if DM exists it must be non-baryonic.

Particle physicists have postulated many possible candidates for non-baryonic DM particles. These include neutrinos, primordial black holes (PBHs), magnetic monopoles, neutalinos and photinos. However, many of these have been effectively ruled out by research e.g. Gaggero et al (2016) who concluded that PBHs couldn't account for more than 20% of DM in the universe. Two of the most popular non-baryonic DM candidates currently

are: Axions and Weakly Interacting Massive Particles (WIMPs). These are both hypothetical particles invented by particle physicists for other reasons than DM, which relieves cosmologists of having to invent new particles. Axions arise from a problem in quantum chromodynamics but have interesting consequences for cosmology as they are predicted to be stable over cosmological timescales (Bertone and Hooper, 2016) and could therefore theoretically constitute DM. WIMPs have been the source of many theoretical studies of DM and are now considered to be the leading class of DM particles.

There are currently four main approaches to discovering WIMPs. There are ongoing experiments, with ever increasing sensitivity, at CERN, using the Large Hadron Collider. One of the goals of the two detectors, ATLAS and CMS, was specifically to try and discover the nature of DM. It has so far been unsuccessful in that respect. There are also attempts to directly detect WIMPs in underground DM laboratories worldwide. So far there has been no confirmed detection of WIMPs. Indirect detection of WIMPs is also being carried out in objects such as the galactic centre, galaxy clusters and dwarf galaxies i.e. objects with a predicted over-density of WIMPs. Again, there has been no confirmed detection.

An interesting fourth approach to the hunt for DM is to discover dark stars. It is predicted that the first stars to form in the early universe, redshift $z \approx 10-50$, may have been comprised of mainly hydrogen and helium and yet were powered by DM heating rather than nuclear fusion. These are believed to have formed when the universe was much denser than now and consisted of high density DM halos. It is hoped that the James Webb Space Telescope will be able to detect dark stars and so enable us to study WIMPs in more detail.

With the advent of numerical simulations, models that involve DM have been extensively explored. Currently a very popular model of the evolution of structure in the universe is the Lambda Cold Dark Matter (ΛCDM) model. Computer simulations have shown that if the DM particles are relativistic ("hot") then, on small scales, density fluctuations are Silk damped, or washed out, the random thermal motion of DM particles. This results in small scale structure fluctuations to be suppressed. However, if the DM particles are "cold" i.e. cold dark matter (CDM), then they undergo a very different structure formation because they have smaller free-streaming length and can form low mass halos which can gradually build up into larger DM structures. These DM structures provide a gravitational well that baryonic particles can fall into to form baryonic structure. This results in a bottom-up process of structure formation which is very different to the top-down sequence predicted for hot DM. These simulations have further convinced cosmologists that CDM comprised of WIMPs are the best explanation for

the growth of large scale structure in the universe. In fact, the ΛCDM model agrees so well with observations that it is often regarded as the "standard model of cosmology".

Even though the evidence for DM is growing, there has been no confirmed detection of DM or WIMPs and the theory of DM leads to a number of problems (Sellwood and Kosowsky, 2000) which I don't have space to detail here. This has led some cosmologists to believe that the Newtonian theory of gravity may need to be amended. This theory is called Modified Newtonian Dynamics (MOND). It is a conceptually simple idea but it has some far-reaching consequences. The basic idea is that Newton's second law be amended from $F = ma$ to $F = ma^2/a_0$ in the limit of very low accelerations ($a << a_0 \approx 1.2 \times 10^{-10} m/s^2$). This could then account for the observed motions of stars within galaxies without having to introduce DM. MOND has been quite successful with explaining flat rotation curves but less successful with galaxy clusters. MOND, however, is not without its own problems particularly when it comes to integrating MOND with General Relativity, explaining the growth of large scale structure, and explaining the first CMB acoustic peak. It would appear that either the LHC, or any detection methods previously described, will eventually detect WIMPs and confirm the existence of DM and MOND will die out as a theory or, if no detection of DM is forthcoming then the theory of MOND may well grow.

3   Dark Energy

DE and cosmic acceleration is arguably one of the greatest unsolved problems in contemporary physics. DE actually has a longer history than DM. As Einstein was forming his field equations for general relativity he realised that this would result in a universe that would gravitationally attract and therefore contract. He therefore introduced the cosmological constant to balance gravity and ensure a static universe. When observations by Hubble in 1929 revealed that the universe is expanding, Einstein referred to his failure to predict a dynamic universe has his biggest blunder. The cosmological constant therefore fell into disuse. However, in 1980 Alan Guth and Alexei Starobinsky proposed the idea of cosmic inflation which involved an exponential expansion of the universe immediately after the Big Bang. The theory of inflation involves a negative pressure field which creates a repulsive force. This idea is similar to DE, however even when inflation became widely accepted the cosmological constant was considered irrelevant. This changed however in 1998 when observations of supernovae revealed that the universal expansion is accelerating. This was the first direct evidence of DE.

Type Ia supernovae occur when a white dwarf in a binary pair accretes enough mass so that it goes over the Chandrasekhar mass and triggers a supernova. The supernova therefore doesn't depend on the mass of the white dwarf on the other star in the binary. Type Ia supernovae can be considered as standard candles and enable astronomers to obtain a luminosity distance. To measure cosmic expansion the apparent magnitude of distant supernovae are compared to those of more local supernovae which are not affected by DE. The Supernova Cosmology Project which carried out one of the surveys in 1998 found that, flat cosmology ($\Omega_\Lambda + \Omega_m = 1$), that $\Omega_m = .28$ and so that $\Omega_\Lambda = .72$. Ω is the density parameter and is defined as the ratio of the observed density to the critical density. Ω_m here is the proportion of matter in universe (DM and baryonic) whilst Ω_Λ represents the proportion of DE in universe. The deceleration parameter is calculated as follows:

$$\frac{1}{2}(\Omega_m - 2\Omega_\Lambda + 2\Omega_R) \tag{1}$$

This then results in a negative deceleration parameter indicating that the expansion of the universe is accelerating. Since 1998 there have been many more supernova surveys and it is has become an active area of observational cosmology. All this supernova data indicates that the apparent luminosity of Type Ia supernovae declines more rapidly with increasing redshift than would be expected if $\Omega_M = 1$ and $\Omega_\Lambda = 0$ i.e. an Einstein-de Sitter universe, or the luminosity distance is greater than expected. Of course, this data could be interpreted as being due to other effects such as dust. More evidence is required.

Although it doesn't directly constrain DE, data obtained from CMB anisotropies does provide accurate figures for parameters that are needed in order to study DE. By measuring anisotropies within the CMB data, from WMAP and Planck satellites, accurate figures for Ω_B and Ω_{DM} have been obtained. Similarly, Baryonic Acoustic Oscillations (BAO) also help the study of DE by constraining cosmological parameters. BAOs are regular and periodic fluctuations in the density of baryonic matter. In a similar way that Type Ia supernovae are standard candles, BAOs are standard rulers. By comparing the clustering of galaxies today (using redshift surveys like SDSS) and comparing it with data from CMB cosmologists have a way of measuring DE that is independent of the supernova method.

Unlike DM, where particle physicists and cosmologists have established theories as to what it is comprised of, the nature of DE is completely unknown. DE is often referred to as vacuum energy. According to quantum field theory a vacuum or empty space actually consists of virtual particles. It has been suggested that these virtual particles may give rise to DE. However,

the density of virtual particles is about 120 times larger than the DE density. There is currently no explanation for this. The DE density is believed to be $\approx 10^{-27} kg/m^3$ which is low but it has such a profound effect on the universe because it fills all of empty space.

There are many theories for DE. However, the simplest one is that it is constant i.e. a cosmological constant. The cosmological constant has a negative pressure equal to its energy density and so exerts a repulsive force causing the expansion of the universe to accelerate i.e. $P = -\rho$. The previously mentioned ΛCDM model uses this form of DE and is the currently preferred cosmological model. An important parameter in the study of DE is the equation of state parameter ω. This comes from:

$$P = \omega \rho c^2 \tag{2}$$

where P is pressue, ρ is density, c is speed of light and ω is the equation of state parameter.

$$\dot{\rho} + 3\frac{\dot{R}}{R}\left(1 + \omega\right)\rho = 0 \tag{3}$$

$$\rho \propto R^{-3(1+\rho)} \tag{4}$$

In the ΛCDM model ω is assumed to be -1.

Another theory of DE is quintessence. In this theory, DE is assumed to be a scalar field and unlike the cosmological constant can vary in time and space. However, there is currently no evidence to support this theory. It has been suggested that instead of vacuum energy, cosmic acceleration can be explained by a modified version of GR. Tests of GR within the solar system have proven the theory to be accurate but it may be the case that GR breaks down on cosmological scales. However there currently is no viable theory of GR that can fully explain cosmic acceleration without introducing some form of DE. However, this doesn't preclude a theory arising in the future as, for example, it wasn't until the advent of GR in 1915 that the precession of Mercury's orbit could be fully explained.

The Dark Energy Survey (DES) was specifically created to probe DE. Using a wide-field camera on the 4m Blanco Telescope in Chile the project aims to catalogue 300 million galaxies. The main goals of the survey are to characterise DE and DM and also to test alternative theories of gravity. The survey takes photometric redshifts of galaxies and also carries out galaxy-galaxy weak lensing measurements i.e. where both the lenses and sources are galaxies. It is also carrying out a time domain survey of Type Ia supernovae. Last year the project reported that they had constrained $\Omega_m = 0.31 \pm 0.09$. The Sloan Digital Sky Survey (SDSS) is also carrying out DE probes with the Extended Baryon Oscillation Spectroscopic Survey (eBOSS). The main

goals of eBOSS are to measure clustering on large scales and to measure BAOs. Other projects include Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) and the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX). One of the aims of Pan-STARRS was to constrain the equation of state parameter for DE (ω) which was found to be $\omega = -1.14$ (Zheng et al, 2014). The Hobby-Eberly Telescope has recently been upgraded for HETDEX and will probe DE through spectrographs of galaxies over the redshift $0 < z < 4$ and also analysing BAOs. The aim of HETDEX is to provide a direct detection of DE at $z \approx 3$ (Hill et al, 2008).

DE may well have a profound effect on the final fate of the universe. Observations suggest that the expansion of the universe will continue to accelerate forever and so the universe will cool as it expands. Redshift will eventually stretch photons to undetectable wavelengths and star formation will cease as gas supply runs out. As stars will eventually die out one by one leaving stellar remnants. Some theories even predict that stellar remnants will disappear due to proton decay leaving only black holes, which themselves will eventually disappear due to Hawking radiation. Hawking radiation is blackbody radiation believed to be emitted by black holes because of quantum effects near the event horizon. This is often referred to as the heat death of the universe.

References

Abott, T., et al (Dark Energy Survey Collaboration), 2015, The Dark Energy Survey: more than dark energy - an overview, arXiv:1601.00329v3

Arun, K., Gudennavar, S., B., Sivaram, C., 2017, Dark Matter, Dark Energy, and Alternate Models: A Review, arXiv:1704.06155

Baldry, I., Cosmology lecture notes - MSc AStrophysics, 2016, Not in public domain

Bergstrom L., 2012, Dark Matter Evidence, Particle Physics Candidates and Detection Methods, arXiv:1205.4882

Bertone, G., Hooper, D., Silk, J., 2004, Particle Dark Matter: Evidence, Candidates and Constraints, arXiv:hep-ph/0404175v2

Bertone, G., Hooper, D., 2016, A History of Dark Matter, arXiv:1605.04909v2

Calmet, X., Kuntz, I., 2017, What is modified gravity and how to differentiate it from particle dark matter?, arXiv:1702.03832v2

Clowe, D., Bradac, M., Gonzalez, A., H., Markevitch, M., Randall, S., W., Jones, C., Zaritsky, D., 2006, A Direct Empirical Proof of the Existence of Dark Matter, arXiv:astro-ph/0608407v1

Cohen-Tannoudji, G., 2015, The dark universe and quantum vacuum, arXiv:1507.00460

Fornengo, N., 2017, Dark matter overview, arXiv:1701.00119v3

Freese, K., 2017, Status of dark matter in the universe, arXiv:1701.01840v1

Gaggero, D., Bertone, G., Calore, F., Connors, R., M., T., Lovell, M., Markoff, S., Storm E., 2016, Searching for Primodial Black Holes in the radio and X-ray sky, arXiv:1612.00457v1

He, H., Zhang, Z., 2017, Direct Probe of Dark Energy through Gravitational Lensing Effect, arXiv:1701.03418v2

Hill,G., J., et al, 2008, The Hobby-Eberly Telescope Dark Energy Experiment (HETDEX): Description and Early Pilot Survey Results, arXiv:0806.0183v1

Li, M., Li., X.,Wang, S., Wang, Y., 2012, Dark Energy: a Brief Review, arXiv:1209.0922v1

Liddle, A.,2015, An Introduction to Modern Cosmology, Wiley and Sons, 3rd Edition

Lisante M, 2016, Lectures on Dark Matter Physics, arXiv:1603.03797v2

Mortonson, M., J., Weinberg, D., H., White, M., 2013, Dark Energy: A Short Review, arXiv:1401.0046v1

Sellwood, J., A., Kosowsky, A., 2000, Does Dark Matter Exist?, arXiv:astro-ph/0009074v1

de Swart, J., Bertone, G., van Dongen, J., 2017, How Dark Matter Came to Matter, arXiv:1703.00013v1

Novosyadlyj, B., Pelykh, V., Zhuk, A., 2013, Dark Energy: Observational Evidence and Theoretical Models, arXiv:1502.04177

Weinberg, S., 2008, Cosmology, Oxford, 1st Edition

Weinberg, D., H., Mortonson, M., J., Eisenstein, D., J.,Hirata, C., Riess, A., G., Rozo, E., 2013, Observational Probes of Cosmic Acceleration, arXiv:1201.2434v2

Zheng, W., Li, S., Xia, J., Li, M., Lu, T., 2014, Constraints on Dark Energy new New Observations including Pan-STARRS, arXiv:1405.2724v2