The Invisible Universe
Transcript

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THE INVISIBLE UNIVERSE

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1) Evidence of Dark Matter in Galaxy Clusters

The first evidence of a large amount of unseen matter came from observations made by Fritz Zwicky in the 1930's. He studied the Coma cluster of galaxies, 321 million light years distant, and observed that the outer members of the cluster were moving at far higher speeds than were expected. He was able to measure the velocities away from us by using the shift in the spectral lines of the galaxy:

When the spectra of galaxies were first observed in the early 1900's it was found that their observed spectral lines, such as those of hydrogen and calcium, were shifted from the positions of the lines when observed in the laboratory. In the closest galaxies the lines were shifted toward the blue end of the spectrum, but for galaxies beyond our local group, the lines were shifted towards the red. This effect is called a **redshift** or**blueshift** and the simple explanation attributes this effect to the speed of approach or recession of the galaxy, similar to the falling pitch of a receding train whistle, which we know of as the Doppler effect. For speeds which are small compared to the speed of light, then the simple formula:

$$\Delta f/f = \Delta\lambda/\lambda = v/c$$

may be used. Here, f is the frequency, λ is the wavelength, Δf and Δλ are changes in frequency and wavelength, v is the velocity of approach or recession and c is the speed of light.

The redshift in the spectral lines from a distant galaxy (below) relative to those observed in our Sun (above).

Suppose a cluster of galaxies were created which were not in motion. Gravity would cause them collapse down into a single giant body. If, on the other hand, the galaxies were initially given very high speeds relative one to another, their kinetic energy would enable them to disperse into the Universe and the cluster would disperse, just as a rocket travelling at a sufficiently high speed could escape the gravitational field of the Earth. The fact that we observe a cluster of galaxies many billions of years after it was created implies that that there must be an equilibrium balancing the gravitational pull of the cluster's total mass and the average kinetic energy of its members. This concept is enshrined in what is called the Virial Theorem so that, if the speeds of the cluster members can be found, it is possible to estimate the total mass of the cluster. Zwicky carried out these calculations and showed that the Coma Cluster must contain significantly more mass than could be accounted for by its visible content.

2) Evidence for an unseen component - Dark Matter - in Spiral Galaxies

In the 1970's a problem related to the dynamics of galaxies came to light. Vera Rubin observed the light from HII regions (ionized clouds of hydrogen such as the Orion Nebula) in a number of spiral galaxies. These HII regions move with the stars and other visible matter in the galaxies but, as they are very bright, are easier to observe than other visible matter. HII regions emit the deep red hydrogen alpha (H-alpha) spectral line. By measuring the Doppler shift in this spectral line, Vera Rubin was able to plot their velocities around the galactic centre as a function of their distance from it. She had expected that clouds that were more distant from the centre of the galaxy (where much of its mass was expected to be concentrated) would rotate at lower speeds - just as the outer planets travel more slowly around the Sun. This is known as Keplerian motion, with the rotational speed decreasing inversely as the square root of the distance from centre. (This is enshrined in Kepler's third law of planetary motion and can be derived from Newton's law of gravity.)

To her great surprise, Rubin found that the rotational speeds of the clouds did not decrease with increasing distance from the galactic centre and, in some cases, even increased somewhat. Not all the mass of the galaxy is located in the centre but the rotational speed would still be expected to decrease with increasing radius beyond the inner regions of the galaxy although the decrease would not be as rapid as if all the mass were located in the centre. To give a concrete example; the rotation speed of our own Sun around the centre of the Milky Way galaxy would be expected to be about 160km/sec. It is, in fact, ~ 220km/sec. The only way these results can be explained is that either the stars in the galaxy are embedded in a large halo of unseen matter - extending well beyond the visible galaxy - or that Newton's law of gravity does not hold true for large distances. The unseen matter whose gravitational effects her observations had discovered is further evidence of "Dark Matter".

The Galactic Rotation Curve for the galaxy NGC 1530.

A modified form of Newton's law called MOND (MOdified Newtonian Dynamics) was proposed by Mordechai Milgrom in 1981 who pointed out that Newton's Second Law (**F=ma**) when applied to gravitational forces has only been verified when the gravitational acceleration is large and has never been verified where the acceleration, **a,** is extremely small - as would be the case for stars towards the edge of a galaxy where the gravitational forces are very weak. With a suitable choice of parameters the observed rotation curves of galaxies can be accurately modelled by the MOND theory; however it has a much harder task explaining other observations that support the existence of dark matter, such as the dynamics of galaxy clusters and gravitational lensing, so MOND will not be considered further.

3) Weighing a Galaxy - there is more mass than we can observe.

The observations of the hydrogen line described above can be used to calculate the mass of a galaxy. The figure below shows the hydrogen line spectrum of the nearby galaxy M33 which lies at a distance of 2.36 x 10^{22}m (~2.9 million light years).

The Hydrogen Line spectrum of M33 in Triangulum.

The horizontal axis of figure 8.18 has been converted from frequency to velocity using the Doppler formula: $\Delta f / f = v/c$. The hydrogen line spectrum of M33 has a width in frequency due to the fact that it is rotating - one side of the galaxy is coming towards us whilst the other is moving away. The centre of the M33 hydrogen emission corresponds to a velocity of -180 km/sec. You might well deduce that the galaxy as a whole is moving *away* from us at this speed but, as all but a few galaxies are moving away from us, the sign convention that is used is that galaxies moving away from us are given positive velocities and those moving towards us are given negative velocities. So this indicates that M33 is moving *towards* us at a speed of ~180 km/second. However, our solar system is moving around the centre of the galaxy at a speed of ~ 220 km/sec and, having corrected for this, M33 is actually moving towards the Milky Way galaxy at a speed of ~ 24 km/sec.

The width of the spectral line is ~200 km/sec so that the hydrogen at the edge of the galaxy is apparently moving around the centre at a speed of 100km/sec. However, though the galaxy is presumably circular, its dimensions on a photographic plate are ~71 x 45 arc minutes. This implies that it is inclined to our line of sight at an angle of arcsin (45 / 71) = ~39 degrees. As a result, the value we measure will be less than the true value due to the projection effect. (If the galaxy were perpendicular to us, we would not observe any rotational width in the hydrogen line spectrum.) The true rotational velocity of the outer parts of the galaxy about its centre should thus be close to 100 **/** sin(39) km/sec = 158 km/sec.

Knowing the distance of the galaxy and its angular size we can calculate its radius.

M33 is ~ 71 arc minutes across which is 71 **/** (60 x 57.3) = 0.020 radians. It lies at a distance of 2.36 x 10^{22} m.

The radius of M33 is thus ~ 0.5 x 0.020 x 2.36 x 10^{22} m.

= ~ 2.4 x 10^{20} m.

If the mass distribution of the galaxy is symmetrical then the gravitational effect on the hydrogen gas at the edge of the galaxy is the same as if all of the galaxy's mass were concentrated at its centre. One can thus use an identical method as was used to calculate the mass of the Sun:

The gravitational force on a small mass at this distance must equal the centripetal acceleration.

$$G M m / r^2 = m v^2 / r$$

(M = mass of Galaxy. m = mass of a small volume of hydrogen. r = distance of the hydrogen from centre of the galaxy. v = velocity of hydrogen around the centre)

This gives:

$$\begin{aligned} M &= r v^2/G \\ &= 2.4 \times 10^{20} \times (1.58 \times 10^5)^2 / 6.67 \times 10^{-11} \text{ kg} \\ &= 9 \times 10^{40} \text{ kg} \\ &= 9 \times 10^{40} / 2 \times 10^{30} \text{ solar masses} \\ &= \sim 45 \text{ thousand million solar masses.} \end{aligned}$$

We have another method of estimating the mass using what is termed the "mass to light ratio" of stars. This is simply the ratio between the mass of a star or star cluster divided by its luminosity - our Sun has, by definition, a mass of 1 and a luminosity of 1 so its mass to light ratio is 1. One could assume that all the stars in M33 were similar to our Sun in terms of their mass to light ratio. If we then calculate the luminosity of M33 compared to that of our Sun we will directly get an estimate of the mass of M33 in solar masses.

The absolute magnitude of the Sun is 4.8 and that of M33 is -19.5, a difference of 24.3 magnitudes. This corresponds to a difference in luminosity of $2.512^{24.3} = \sim 5.2 \times 10^9$ which gives a mass estimate of ~5 thousand million solar masses. This is a factor of 10 less than the value derived above. M33 obviously has mass which does not emit light such as dust and gas and not all stars will have the same mass to light ratio as our Sun - hot stars are very luminous for their mass compared to our Sun and cooler stars (of which there are many more) less luminous. The average mass to light ratio for stars, gas and dust in our own galaxy is ~1.5 so, assuming a similar mix, this would give M33 a mass of ~8 thousand million solar masses.

The fact that this is still a factor of ~ 6 less than that derived dynamically is further evidence of the presence of dark matter in the galaxy - there appears to be ~5 times as much dark matter than normal matter in the makeup of the galaxy!

4) Ripples in the Cosmic Microwave Background and the formation of galaxies

It was the American physicist, George Gamow, who first realised that the Big Bang should have resulted in radiation that would still pervade the universe. This radiation is now called the **Cosmic Microwave Background** (CMB). Initially in the form of very high-energy gamma rays, the radiation became less energetic as the universe expanded and cooled, so that by a time some 300 to 400 thousand years after the origin the peak of the radiation was in the optical part of the spectrum.

Up to that time the typical photon energy was sufficiently high to prevent the formation of hydrogen and helium atoms and thus the universe was composed of hydrogen and helium nuclei and free electrons - so forming a **plasma**. The electrons would have scattered photons rather as water droplets scatter light in a fog and thus the universe would have been opaque. This close interaction between the matter and radiation in the universe gave rise to two critical consequences: firstly the radiation would have a black body spectrum corresponding to the then temperature of the universe and secondly that the distribution of the nuclei and electrons (normal matter) would have a uniform density except on the very largest scales.

We will return to the second consequence later, but now will continue with the first. As the universe expanded and cooled there finally came a time, ~ 380,000 years after the origin, when the typical photon energy became low enough to allow atoms to form. There were then no free electrons left to scatter radiation so the universe became transparent. This is thus as far back in time as we are able to see. At this time the universe had a temperature of ~3,000K. Since that time, the universe has expanded by about 1,000 times. The wavelengths of the photons that made up the CMB will also have increased by 1,000 times and so will now be in the far infrared and radio part of the spectrum - but would still have a black body spectrum. The effective black body temperature of this radiation will have fallen by just the same factor and would thus now be ~ 3K.

The "ripples" in the Cosmic Microwave Background.

Observations by the COBE spacecraft first showed that the CMB did not have a totally uniform temperature and, since then, observations from the WMAP spacecraft, balloons and high mountain tops have been able to make maps of these so called "ripples" in the CMB - temperature fluctuations in the observed temperature of typically 60 micro Kelvin.

All-sky map of the CMB ripples produced from 5 years of WMAP data in March 2008.

As described above, for ~380,000 years following the big bang, the matter and radiation were interacting as the energy of the photons was sufficient to ionize the atoms giving rise to a plasma of nuclei and free electrons. This gives rise to two results:

1) The radiation and matter were in thermal equilibrium and the radiation will thus have had a black body spectrum.

2) The plasma of nuclei and electrons will have been very homogeneous as the photons acted rather like a whisk beating up a mix of ingredients.

It is the second of these that is important to the argument that follows. When the temperature drops to the point that atoms can form, the matter can begin to clump under gravity to form stars and galaxies. Simulations have shown that, as the initial gas is so uniformly distributed, it would take perhaps 8 to 10 billion years for regions of the gas to become sufficiently dense for this to happen. But we know that galaxies came into existence around 1 billion years after the Big Bang. Something must have aided the process. We believe that this was dark matter that was not composed of normal matter and which is called non-baryonic dark matter. As this would not have been coupled to the radiation, it could have begun to gravitationally "clump" immediately after the Big Bang. Thus when the normal matter became decoupled from the photons, there were "gravitational wells" in place formed by concentrations of dark matter. The normal matter could then quickly fall into these wells, rapidly increasing its density and thus greatly accelerating the process of galaxy formation.

How Dark Matter affects the CMB

The concentrations of dark matter that existed at the time the CMB originated have an observable effect due to the fact that if radiation has to "climb out" of a gravitational potential well it will suffer a type of red shift called the "gravitational red shift". So the photons of the CMB that left regions where the dark matter had clumped would have had longer wavelengths than those that left regions with less dark matter. This causes the effective blackbody temperature of photons coming from denser regions of dark matter to be less than those from sparser regions - thus giving rise to the temperature fluctuations that are observed. As such observations can directly tell us about the universe as it was just 380,000 or so years after its origin it is not surprising that they are so valuable to cosmologists!

There must be missing mass!

Observations of the Cosmic Microwave Background confirm and supporting evidence, enable us to calculate the average density and the total mass/energy content of the visible Universe. If the total mass was M, then it appears that the best estimate of the mass of the visible matter, stars and excited gas, is about 0.01M. 99% of the content of the Universe is invisible! The first question to ask is whether this invisible content is normal (baryonic) matter that just does not emit light such as gas, dust, or objects such as brown dwarfs, neutron stars or black holes. These latter objects are called MACHOs (Massive Astronomical Compact Halo Objects) as many would reside in the galactic halos that extend around galaxies.

There are two pieces of evidence that indicate that the total amount of normal matter in the Universe is only ~ 4% of the total mass/energy content. The first depends on measurements of the relative percentages of hydrogen, helium and lithium and their isotopes that were formed in the big bang. These are very sensitive to the baryon to photon ratio and put an upper limit of baryonic matter at about 4%. The second line of evidence is that if a significant amount of mass were in the form of MACHOs then gravitational micro lensing studies (as have discovered a number of planets) would have detected them. Though we know that, for example, pulsars are found in the galactic halo the total mass of these and other MACHOs cannot explain the missing matter. So we still have to account for ~96% of the total mass/energy content of the Universe! From several lines of observational evidence it is believed that a substantial part of this is in the form of non-baryonic dark matter - usually just called dark matter.

5) Gas Entrapment

NASA's Chandra X-ray observatory has revealed that the elliptical galaxy, NGC 4555 is embedded in a cloud of gas having a diameter of about 400,000 light years and a temperature of 10 million degrees Celsius. At this temperature the molecules of gas would be traveling at very high speeds and the mass of the stars within the galaxy would be far to low to prevent its escape. For the gas to remain in the vicinity of the galaxy the total mass of the system must be about 10 times the combined mass of the stars in the galaxy and about 300 times that of the gas cloud.

NASA'a Chandra X-Ray satellite image of hot gas surrounding the galaxy NGC 4555.

6) Gravitational Lensing

Massive object in space distort the space around them and bend the light that passes near to them. This has the effect of forming what is called a gravitational lens. We can observe the lensing effect of single stars (and even planets!) and single galaxies. On a much larger scale the mass of a cluster of galaxies can distort the images of more distant objects. The image of the Abell Cluster 2218 is a wonderful example showing images of more distant galaxies that have been distorted into arcs. The amount of distortion will be a function of the total mass of the intervening cluster, so this gives a way of estimating the total mass of galaxy clusters, confirming the existence of dark matter. Using this technique, astronomers have even shown how the distribution of dark matter has become more "clumpy" over the last 6 billion years.

The Abell 2218 cluster imaged by the Hubble Space Telescope

How much non-baryonic dark matter is there?

There are several ways of estimating the amount of dark matter. One of the most direct is based on the detailed analysis of the fluctuations in the Cosmic Microwave Background. The percentage of dark matter has an observable effect, and the best fit to current observations corresponds to dark matter making up ~ 23% of the total mass/energy content of the Universe. Other observations support this result. This the leaves two further questions: what is dark matter and what provides the remaining 73% of the total mass/energy content?

What is Dark Matter?

The honest answer is that we do not really know. The standard model of particle physics does not predict its existence and so extensions to the standard theory (which have yet to be proven) have to be used to predict what it might be and suggest how it might be detected.

Dark matter can be split into two possible components: Hot Dark Matter would be made up of very light particles moving close to the speed of light (hence hot) whilst Cold Dark Matter (CDM) would comprise relatively massive particles moving more slowly. Simulations that try to model the evolution of structure in the Universe - the distribution of the clusters and super clusters of galaxies - require that most of the dark matter is "cold" but astronomers do believe that there is a small component of hot dark matter in the form of neutrinos. There are vast numbers of neutrinos in the Universe but they were long thought to have no mass. However, recent observations attempting to solve the solar neutrino problem discussed earlier, show that neutrinos can oscillate between three types; electron, tau and muon. This implies that they must have some mass but current estimates put this at less than 1 millionth of the mass of the electron. As a result they would only make a small contribution to the total amount of dark matter - agreeing with the simulations.

A further confirmation of the fact that hot dark matter is not dominant is that, if it were, the small scale fluctuations that we see in the WMAP data would have been 'smoothed' out and the observed CMB structure would have shown far less detailed structure.

Axions

One possible candidate for cold dark matter is a light neutral axion whose existence was predicted by the Peccei-Quinn theory in 1977. There would be of order 10 trillion in every cubic centimetre! If axions exist they could theoretically change into photons (and vice versa) in the presence of a strong magnetic field. One possible test would be to attempt to pass light through a wall. A beam of light is passed through a magnetic field cavity adjacent to a light barrier. A photon might rarely convert into an axion which could easily pass through the wall where it would pass through a second cavity where (again with an incredibly low probability) it might convert back into a photon!

Another experiment at Lawrence Livermore Laboratory is searching for microwave photons within a tuned cavity that might result from an axion decay, whilst in Italy polarised light is being passed back and forth millions of times through a 5 tesla field. If axions exist, photons could interact with the field and become axions; causing a very small anomalous rotation of the plane of polarisation. The most recent results do indicate the existence of axions with a mass of ~ 3 times that of the electron, but this has to be confirmed and there may well be other causes for the observed effect on the light.

WIMPS

An extension to the standard model of particle physics called "super symmetry" suggests that WIMPS (Weakly Interacting Massive Particles) might be a major constituent of CDM. A leading candidate is the neutralino - the lightest neutral super symmetric particle. Billions of WIMPS could be passing through us each second! Very occasionally they will interact with the nucleus of an atom making it recoil - rather like the impact of a moving billiard ball with a stationary one. In principle, but with very great difficulty, these interactions can be detected.

Though a million WIMPS might pass through every square cm of the Earth each second, they will very rarely interact with a nucleus of a heavy atom. It is estimated that within a 10 kilogram detector only one interaction might occur, on average, each day. To make matters worse we are being bombarded with cosmic rays which, being made of normal matter, interact very easily. Any WIMP interactions would be totally swamped! One way to greatly reduce the number of cosmic rays entering a detector is to locate it deep underground - such as at the bottom of the Boulby Potash Mine in north Yorkshire at a depth of 1100m. At this depth, the rock layers will have stopped all but one in a million cosmic rays. In contrast, only about three in a billion WIMPs would have interacted with nuclei in the rock obove the detector.

To make matters worse, natural radioactivity in the rocks surrounding the experimental apparatus increases the "noise" which can mask the WIMP interactions, so the detectors are surrounded by radiation shields of high purity lead, copper wax or polythene and may be immersed within a tank of water. The chosen detectors may also emit alpha or beta particles so care must be taken over the materials from which they are made. Photomultiplier tubes (to detect scintillation) cause a particular problem and "light guides" are used to transfer the light from the crystal, such as sodium iodide, in which the interaction takes place to the shielded photomultiplier tube.

Possible Success?

One possible way to show the presence of WIMP interactions in the presence of those caused by local radioactivity is due to the fact that, in June, the motion of the Earth around the Sun (29.6 km/sec) is in the same direction as that of the Sun in its orbit around the galactic centre (232 km/sec). So the Earth would sweep up more WIMPS than in December when the motions are opposed. The difference is ~7%, so one might expect to detect more WIMPs in June than in December. As the number of interactions from local radioactivity should remain constant, this gives a possible means of making a detection. In the DArk MAtter (DAMA) experiment at the Gran Sasso National laboratory, 1400 m underground in Italy, observations have been made of scintillations within 100 kg of pure sodium iodide crystals. The results of 7 annual cycles have given what is regarded as a possible detection but, again, there may be other explanations.

Possible evidence from PAMELA?

An instrument package called PAMELA is currently flying on a Russian Earth orbiting

Satellite. As officially reported on November 5th 2008, it has detected an excess of high energy positrons observed coming from the centre of our galaxy. This excess, the authors of the Nature paper say, 'may constitute the first indirect evidence of dark-matter particle annihilations'. They could be the result of an interaction between two dark matter particles. There would be expected to be a major concentration of dark matter towards the centre of the galaxy, although they add that there could yet be other explanations, such as the presence of a nearby pulsar.

How much Normal and Dark Matter is there and what else must there be?

Normal and Dark matter can between them account for some 27% of the total mass-energy of the universe. It appears that the majority, some 73%, must be something else. It is thought to be a form of energy - **we call Dark Energy** - latent within space itself that is totally uniform throughout space. In fact this could be exactly what was invoked by Einstein to make his "static" universe - the cosmological constant or Lambda (Λ) term. A positive Λ term can be interpreted as a fixed positive energy density that pervades all space and is unchanging with time. Its net effect would be repulsive. There are, however, other options and a range of other models are being explored where the energy is time dependent. These are given names such as "quintessence", meaning 5th force. As the total amount of this energy and its repulsive effects are proportional to the volume of space, the effects of dark energy should become more obvious as the Universe ages and its size increases.

In the "Big Bang" models of the Universe, the initial expansion slows with time as gravity reins back the expansion, and the expansion rate would never increase. However if there is a component in the Universe whose effect is repulsive and increasing with the volume of space, the scale size of the Universe will vary in a quite different way with time. Initially, when the volume of the Universe is small, gravity will dominate over dark energy and the initial expansion rate of the Universe will slow - just as in the "Big Bang" models, but there will come a point when the repulsive effects of the dark energy will equal and then overcome gravity and the Universe will begin to expand at an ever increasing rate. If this is the case, distant galaxies will be further away from us than would have been the case in the "Big Bang" models.

Evidence for Dark Energy

In the 1990's it became possible to measure the distance to very distant galaxies. We can estimate the distance to remote objects if we have what is called a standard candle - an object of known brightness some of which have been observed at known distances nearby. Hubble used such a technique to measure the distances of galaxies using Cepheid variable stars of known peak brightness. These had first been observed in the Small Magellanic Cloud (SMC) at a known distance from us. Suppose one of these stars is observed in a distant galaxy and appears 10,000th as bright as a similar Cepheid in the SMC. Assuming no extinction by dust it would, from the inverse square law, be at 100 times the distance of the SMC.

But, though Cepheid variable stars are some of the brightest stars known, there is a limit to distances that can be measured by using them. Something brighter is required. For a short time, supernovae are the brightest objects in the Universe and there is one variant, called a Type 1a supernova, that is believed to have a well calibrated peak brightness. It might be useful to consider an analogy. Imagine a ball of plutonium of less than critical mass. If one then gradually added additional plutonium uniformly onto its surface it would, at some point in time, exceed the critical mass and explode. The power of this explosion should be the same each time the experiment is carried out as a sphere of plutonium has a well defined critical mass. As you will see, this is rather similar to what occurs when a Type 1a supernova occurs.

Material accreting onto a white dwarf.

A type 1a supernova occurs in a binary system. The more massive star of the pair will evolve to its final state first and its core may become a white dwarf about the size of the Earth. Later its companion will become a red giant and its size will dramatically increase. Its outer layers may then be attracted onto the surface of the white dwarf whose mass will thus increase. At some critical point, when its mass nears the Chandrasekhar limit of roughly 1.44 times the mass of the Sun, the outer layers will ignite and in the resulting thermonuclear explosion the entire white dwarf star will be consumed. As all such supernovae will explode when they reach the same total mass, it is expected that they will all have similar peak brightness's (about 5 billion times brighter than the Sun) and should thus make excellent standard candles.

Because type Ia supernovae are so bright, it is possible to see them at very large distances. The brightest Cepheid variable stars can be seen at distances out to about 10-20 Mpc (~32 to 64 million light years). Type Ia supernovae are approximately 14 magnitudes brighter than Cepheid variables, and are thus about a quarter of a million times brighter. They can thus be can be seen about 500 times further away corresponding to a distance of around 1000 Mpc - a significant fraction of the radius of the known Universe. However supernovae are rare with perhaps one each 300 years in a typical spiral galaxy. Observations are now observing thousands of distant galaxies on a regular basis and sophisticated computer programs look for supernovae events. Once initially detected, observations continue to look for the characteristic light curve of a type 1a supernova which results from the radioactive decay of nickel-56; first to cobalt-56 and then to iron-56.

Hubble (and later others) plotted the apparent expansion velocity of galaxies against their distance and produced a linear plot. This plot would not be expected to continue linearly out to very great distances due to changes in the expansion rate of the Universe over time. For the critical (or zero curvature) Universe which the CMB observations imply, the curve would have been expected to fall below the linear line for great distances. Observations of distant type Ia supernovae have recently enabled far greater distances to be measured which, together with the corresponding redshifts, have enabled the Hubble plot to be extended to the point where the plot would no longer be linear. As expected, the plot is no longer linear but, to great surprise, the curve falls above the linear extrapolation, not below. This implies that the expansion of the Universe is speeding up - not slowing down as expected - and is thus evidence that dark energy exists.

The nature of dark energy

Dark energy is known to be very homogeneous, not very dense (about 10^{-29} grams per cc) and appears not to interact through any of the fundamental forces other than gravity. This makes it very hard to detect in the laboratory.

The simplest explanation for dark energy is that a volume of space has some intrinsic, fundamental energy as hypothesized by Einstein with his cosmological constant. Einstein's special theory of relativity relates energy and mass by the relation $E = mc^2$ and so this energy will have a gravitational effect. It is often called a vacuum energy because it is the energy density of empty vacuum. In fact, most theories of particle physics predict vacuum fluctuations that would give the vacuum exactly this sort of energy. One can perhaps get some feeling of why a pure vacuum can contain energy by realizing that it is not actually empty! Heisenberg's Uncertainty Principle allows particles to continuously come into existence and (quickly) go out of existence again. A pure vacuum is seething with these virtual particles!

According then to Heisenberg's Uncertainty Principle there is an uncertainty in the amount of energy that can exist. This small uncertainty allows a nonzero energy to exist for short intervals of time defined by:

ΔE x ΔT is of order h/2pi, where h is Planck's Constant equal to 6.626×10^{-34} m^2 kg /s

Because of the equivalence between matter and energy, these small energy fluctuations can produce particles of matter (a particle and its anti-particle must be produced simultaneously) which come into existence for a short time and then disappear. As an example, consider a proton and the anti-proton which have masses of 1.7×10^{-24} grams. If a virtual pair were to be created, their equivalent energy would be (from $e= mc^2$) 3×10^{-3} ergs and thus they could only exist for a time of order 3×10^{-25}seconds.

A number of experiments have been able to detect this vacuum energy. One of these is the Casimir experiment in which, in principle, two metal plates are placed very close together in a vacuum. In practice it is easier to use one plate and one plate which is part of a sphere of very large radius. One way to think of this is that the virtual particles have associated wavelengths - the wave particle duality. Virtual particles whose wavelengths are longer than the separation of the plates cannot exist between them so there are more virtual particles on their outer sides and this imbalance gives the effect of an attractive force between the plates.

An interesting analogy is when two ships sail alongside each other to transfer stores or fuel in the open sea in conditions with little wind but a significant swell. Between them, only waves whose wavelength is smaller than the separation of the hulls can exist but on the outside all wavelengths can be present. This inequality gives rise to a force that tends to push the two ships apart, thus requiring that the ships actively steer away from each other.

The cosmological constant is the simplest solution to the problem of cosmic acceleration with just one number successfully explaining a variety of observations and has become an essential feature in the current standard model of cosmology. Called the **Lambda-CDM model**, as it incorporates both cold dark matter and the cosmological constant, it can be used to predict the future of the Universe.

The makeup of the Universe

The observations of the CMB, type Ia supernovae, Hubble's Constant and the distribution of galaxies in space all now give a consistent model of the universe. It appears that normal matter accounts for just ~4%, dark matter ~23% with the remaining ~73% of the total mass energy content of the universe being in the form of dark energy. Over the next few years, as the CMB observations are refined, we will have pretty accurate values for these percentages.

The scale size of the Universe with time.

The "scale size" figure shows how we believe that the scale size of the universe has changed with time in the past and how it will expand ever faster in the future.

A consequence of this is that, in the far future, the clusters of galaxies that we now see will have been carried over our horizon and will become invisible to us. To anyone observing from our galaxy the universe will eventually appear to be empty apart from the stars in the large amorphous galaxy that will result from the combining of our local group of galaxies - they could not learn much about the universe.

We actually live at the best possible time to learn about our universe, so it's a great time to be an astronomer!