Certificate of Higher Education
in

Astronomy

2008 - 2009

GRAHAM D. FLEMING

Student **840817**

PHAS1513 – Astronomy Dissertation 1

It's Dark – What can the Matter be?

Abstract

Scientific studies of the motions of galaxies and the phenomenon of gravitational lensing have provided evidence to suggest that only about 4% of the total energy density in the universe can be seen directly. Investigating the nature of the remaining 96% has caused the fields of astrophysics and particle physics to unite with a common cause. The missing mass is thought to consist of two invisible components, dark energy and dark matter. This dissertation is a review of current literature and research into the nature of dark matter and its role in the development of our universe.

Department of Physics and Astronomy
UNIVERSITY COLLEGE LONDON

Contents

1. Introduction

The earth was without form and void, and darkness was upon the face of the deep……And God said, "Let there be light"; and there was light. And God saw that the light was good; and God separated the light from the darkness[1].

For the last few thousand years, humanity knew how the world was created. More recently, such knowledge has been challenged, by science.

If we consider a period 13.7 billion years ago, all the matter and energy that we see today, was contained within an infinitesimally small, infinitely dense, hot point in space known as a singularity. In reality there was nothing, neither space nor time existed[2]. When the singularity appeared, it began to inflate and expand rapidly in what is called the Big Bang. Space, time and matter were created in the Big Bang.

Eventually, the universe cooled to a point where photons could escape the ionic plasma, and the universe became transparent. We can now see the radiation spectrum of these photons at the 'surface of last scattering', identified in 1965, by Penzias and Wilson[3] as what is now called the Cosmic Microwave Background (CMB) radiation.

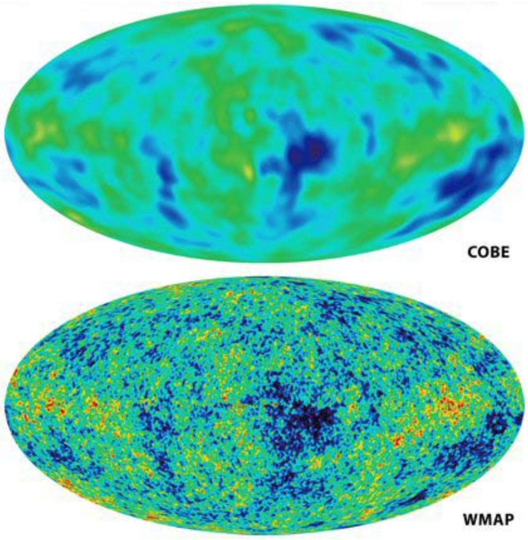


Figure 1 - All-sky images of the early Universe.

Both the Cosmic Background Explorer (COBE) in 1989 and the Wilkinson Microwave Anisotropy Probe (WMAP) in 2001 surveyed the CMB[4] [5], with increasing resolution, producing maps that show how the Universe looked when it was about 380 thousand years old. Although these 'temperature' maps of the CMB are almost uniform, there are extremely small (less than 1 millionth of a degree) variations, called anisotropies, in the 2.73K background temperature. *Figure 1* shows these variations, with warmer regions being coloured red and cooler regions blue.

---

[1] Bible.com

[2] Hawking and Ellis, 1968; Hawking and Penrose, 1970

[3] Penzias, A.A., & Wilson, R.W. 1965.

[4] Smoot, G.F. et al., 1992.

[5] Hinshaw, G. et al., 2008.

One of the predictions of the Big Bang theory is that anisotropies will exist, and that they correspond to areas of varying density in the material of the early universe. It is suggested that, after billions of years, these ‘density clumps’ evolved, through gravitational attraction, into the visible galaxies, stars and planets that we have today.

2. The missing mass problem

Star formation and galaxy growth has continued, with small galaxies merging to form larger galaxies, which then merge into clusters and super clusters.

If the universe was made solely of this luminous matter then it would be possible to calculate its mean density. When this is done, it is found that the luminous matter only contributes about 0.5% of the critical density of the universe.

Critical Density

Critical density defines the average density of matter in the universe today that would be needed to exactly halt the expansion of the universe. WMAP data suggest that, at the present time, the mass density of the universe is close to the critical density, implying that the universe is flat and will eventually stop expanding. The value of critical density (ρ_C) can be derived from the Friedmann Equation[6]:

$$\left[H_0{}^2 - \frac{8}{3}\pi G \rho_c \right] R^2 = -kc^2 \qquad (1)$$

Where, H_0 is the present day Hubble constant (71 km s^{-1} Mpc^{-1}),
G is the Newtonian Gravitational constant (6.674 x 10^{-11} m^3 kg^{-1} s^{-2}),
R is a scaling factor,
k is the curvature parameter, and
ρ_C is the total density of matter, radiation and vacuum energy.

This can be re-stated as:

$$H_0{}^2 = \frac{8\pi G\rho_c}{3} - \frac{kc^2}{R^2} \qquad (2)$$

For a flat universe, the curvature parameter (k) is zero. This then leads to the curvature term (kc^2/R^2) in equation [Eq.(2)] tending to zero, leaving the equation as:

$$H_0{}^2 = \frac{8\pi G \rho_c}{3} \qquad (3)$$

Which can be re-stated in terms of critical density, as

$$\rho_c = \frac{3H_0{}^2}{8\pi G} \qquad (4),$$

giving a critical density value in the order of 0.95 x 10^{-26} kg/m^3 (~5.3 GeV/m^3), which is equivalent to about 5 hydrogen atoms per cubic metre of space. This critical density is made up of three components, i.e.

$$\rho_c = \rho_m + \rho_r + \rho_\Lambda \qquad (5)$$

---

[6] Friedman, A., (1999).

Where, ρ_m is the matter density,
ρ_r is the radiation density, and
ρ_Λ is the vacuum energy density.

By convention, it is more convenient to measure the overall matter-energy density using dimensionless parameters, defined in terms of the critical density. The ratio of the actual mean density (ρ) of the observable universe to the critical density (ρ_C) is denoted by the Greek letter omega (Ω) and is known as the mass density parameter. For a flat universe, with $k = 0$ the mass density parameter will have a value of unity, i.e. $\Omega = 1$.

Re-stating equation [Eq.(5)] for critical density in terms of the mass density parameter gives:

$$\frac{\rho}{\rho_c} = \Omega = \Omega_m + \Omega_r + \Omega_\Lambda \qquad (6)$$

Where, Ω_m is the matter mass density, (assessed by WMAP to be 0.27 ± 0.04),
Ω_r is the radiation mass density, (assessed by WMAP to be 8.24×10^{-5}), and
Ω_Λ is the vacuum energy mass density (0.73 ± 0.04), due to the cosmological constant.

The value of 0.27 ± 0.04 for Ω_m derived from the WMAP data has been found to contain only 0.044 ± 0.004 of ordinary baryonic matter, i.e. only 16.3% of the mass density of the universe. The remaining 83.7% is matter that cannot be seen.

3. Evidence supporting a Dark Matter model

The existence of such 'dark' matter was first suggested by the Swiss astronomer, Fritz Zwicky in 1933 following his study of the Coma cluster of galaxies[7] (*Figure 2*). Using the virial theorem, Zwicky investigated 8 galaxies in the cluster to infer the clusters mass.

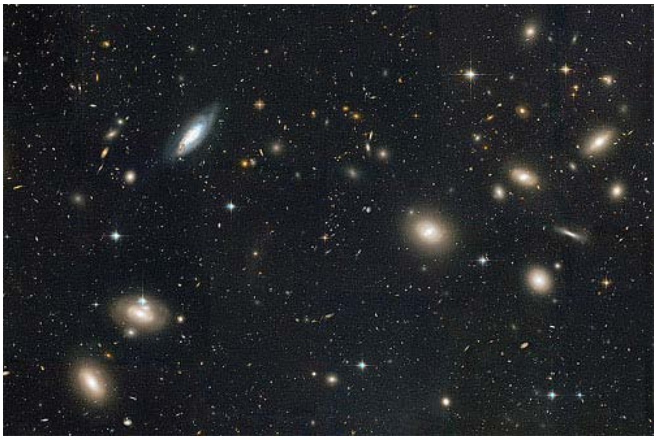


Figure 2 – The Coma cluster of galaxies.

His results indicated that the Coma cluster contained at least 200 times more mass than the visible luminous galaxies suggested. This led Zwicky to conclude that the cluster must contain a large amount of dim, or completely 'dark matter'. Other areas of research have led to a greater understanding of the dark matter phenomenon.

Large Galactic Clusters

By using the Doppler Effect to measure the average speed of each galaxy within a galaxy cluster, their relative motions within the cluster can be seen. If the total mass of all the visible galaxies in the cluster, and their distances apart, are calculated it is possible to work out the gravitational effect necessary to bind the cluster together, and thereby, the escape velocity of the cluster.

Results show that the average galactic speed is far greater than the escape velocity of the clusters involved. In effect, galaxies should not be gravitationally bound within large clusters, implying the presence of some form of unseen matter that is adding to the overall mass of the cluster, preventing it from flying apart.

The rotation curves of galaxies

The Milky Way galaxy has a large central mass surrounded by a disc of matter orbiting in near circular orbits. Kepler's third law states that the more distant an object from the central mass, the slower its average orbital period should be. This is given by the general equation:

$$P^2 = k.a^3 \qquad (7)$$

Where, P is the orbital period,
a is the average distance from the sun, and
k is a constant equal to 1 if P is in years and a is in AU's.

---

[7] Zwicky, F., (1933).

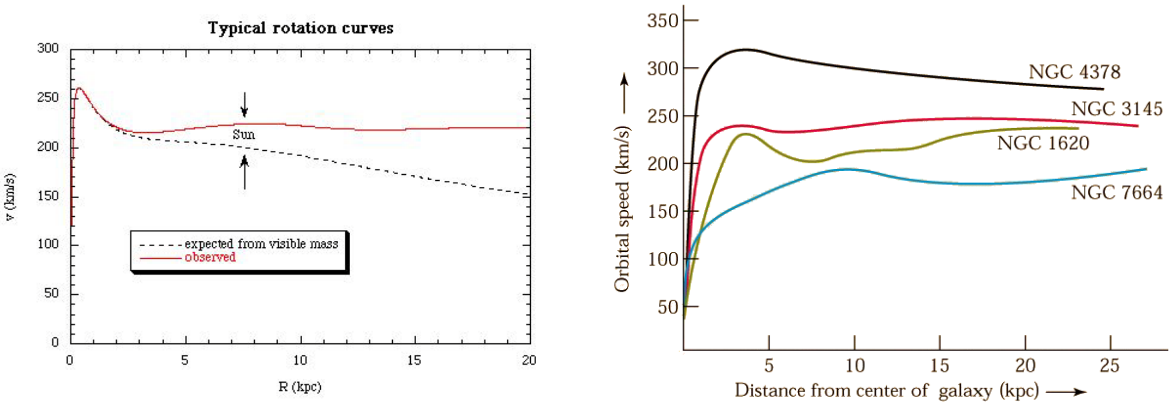
This equation only applies to objects that orbit the Sun. Newton demonstrated that Kepler's third law was linked to his own law of gravity, and re-stated Kepler's law as:

$$P^2 = \left[\frac{4\pi^2}{G\left(m_1 + m_2\right)}\right] a^3 \qquad (8)$$

Where, G is the universal constant of gravity (6.674 x 10^{-11} m^3 kg^{-1} s^{-2}),
m_1 is the mass of the first object, and
m_2 is the mass of the second object.

Newton's form of Kepler's third law is valid whenever two bodies revolve around a common centre of mass due to their mutual gravitational attractions. This means that for any galaxy, the speed at which stars orbit the galactic nucleus depends on their distance from the centre. This distance-speed relationship defines what is known as the galaxies rotation curve. Observing the motion of stars on the visible edges of galaxies it would be expected that their speed is almost proportional to the square of their distance from the centre. Empirical data shows this is not the case, and it would appear that there is a flat rotation curve with very little difference in the speed of rotation for stars near the nucleus and for those on the edges of the galaxy.

Rotational curves are obtained by plotting the Doppler shifts of stars along the length of a galaxy, against their respective distance from the galactic centre. *Figure 3(a)* shows a comparison between the expected rotation curve for our Milky Way galaxies' visible (baryonic) material against its observed rotation[8]. The fact that the rotational velocity does not decrease in the predicted way suggests that the galaxy contains a substantial amount of mass that we cannot see, and that it is exerting a gravitational effect on the baryonic mass of the galaxy. This flattening of the rotation curve is further highlighted in *Figure 3(b)* for those of other galaxies.



(a) For Milky Way *(b) For other galaxies*

Figure 3 – Galactic Rotation curves.

Data from rotation curves indicate that about 90% of a galaxies' mass cannot be seen, and can only be detected through its gravitational effect.

Newton's Law of Universal Gravitation describes the gravitational attraction between bodies with mass and was first proposed in Newton's *Philosophiae Naturalis Principia Mathematica* published in 1687. The law states that:

---

[8] Caldwell, J.A.R., & Ostriker, J.P., 1981.

$$F = G\left[\frac{m_1 \times m_2}{r^2}\right] \qquad (9)$$

Where, F is the force of attraction,
G is the universal constant of gravity (6.674 x 10^{-11} N m^2/kg^2),
m_1 is the mass of the first object,
m_2 is the mass of the second object, and
r is the distance between the two masses.

In simple terms this states that, every point mass attracts every other point mass, with a force proportional to the product of the two masses, and inversely proportional to the square of the distance between them.

Some researchers doubt that Newtonian gravitational predictions of motion are correct at galactic scales[9], since they are written in terms of point masses. Their suggestion is that Einstein's Theory of General Relativity should be used when analysing the mass density distributions in the galactic disc (to explain the flattened rotation curves). Other theorists suggest that Newton's Second Law of Motion does not apply when the acceleration is extremely small. In 1983, Mordehai Milgrom proposed that the acceleration of orbiting bodies is more critical than distance, when considering galactic motion. He suggested that there is a critical value of acceleration (10^{-10} m/s^2) below which gravity does not obey the Newtonian model. Milgrom's theory, called Modified Newtonian Dynamics (MOND)[10] [11] states that below the critical threshold, force is inversely proportional to distance (and not distance squared). In this model, orbital speeds remain constant, regardless of distance, thereby accounting for the flat galactic rotational curves.

A recent re-evaluation and adaptation of Newton's equations of gravity[12] to translate Einstein's curved space-time back into equations of force, suggests that effects attributed to dark matter in the Universe can be accounted for by the force of gravity exerted by black holes and by the indirect effects of an increase in the force of gravity shaping large scale structures in the Universe.

As an alternative to Newtonian and Einsteinian theories, MOND is not generally accepted. In a study of the Virgo, Abell 2199, and Coma Clusters[13], MONDs predictions concerning mass-temperature relationships did not agree with measurements made by the ASCA, ROSAT, BeppoSAX, and XMM experiments – in fact, the only way that MOND could be made to fit the measurements was with the addition of large amounts of baryonic (presumably dark) matter. Similar conclusions were drawn in a study mapping dark matter using gravitational lensing[14].

Further empirical evidence indicating that MOND is not the solution was obtained following a study in August 2006[15] which had looked at the matter distribution in two large colliding galaxy clusters known as the Bullet Cluster (1E 0657-56). As the clusters pass through each other the luminous, baryonic matter in one interacts with the baryonic matter in the other, and slows down. At the same time, the dark matter does not interact and passes through without disruption.

---

[9] Cooperstock, F.I., & Tieu, S., 2005.
[10] Milgrom, M., 1983.
[11] Bekenstein, J.D., 2005.
[12] Worsley, A., 2008.
[13] Aguirre, A., Schaye, J., & Quataert, E., 2001.
[14] Massey, R., et al., 2007.
[15] Clowe, D., et al., 2006.

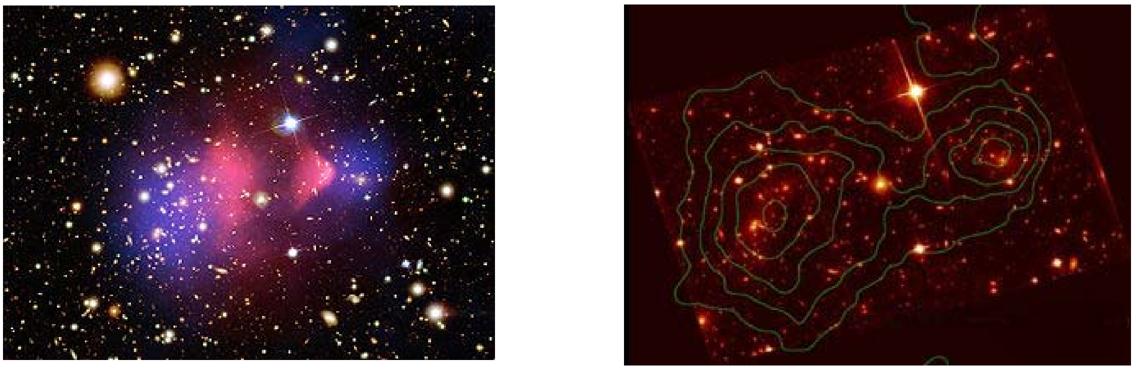


Photo from the Chandra X-ray Observatory showing that the dark matter (blue) has become separated from luminous matter (red.).

Mass density contours superimposed over photograph taken with Hubble Space Telescope.

Figure 4 – The Bullet Cluster.

This can be seen in the composite image (*Figure 4*), the pink areas indicate hot, X-ray emitting gas which contain most of the ordinary baryonic matter. The blue areas show where most of the mass in the colliding galaxy clusters is concentrated, which is also highlighted in the density contour overlay on the right. MOND theorists have accepted that this apparent difference in mass distribution between ordinary and dark matter cannot be explained by a purely baryonic MOND model.

Recent supercomputer simulations[16], have modelled the gravitational influences of the stars and gas that make up our own galaxy. Standard models indicate the presence of roughly spherical halos of dark matter surrounding our Galaxy. The new simulations suggest that the initial halo of dark matter surrounding our galaxy was formed out of dark matter lumps which were then torn apart, creating a disc of dark matter within the Galaxy (*Figure 5*).

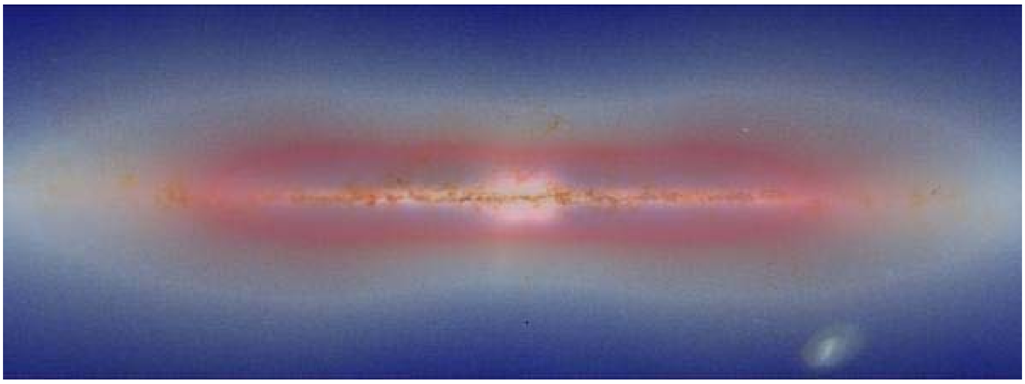


Figure 5 - A composite image of the dark matter disk (red contours) and the Atlas image mosaic of the Milky Way obtained as part of the Two Micron All Sky Survey (2MASS). (Credit: J. Read and O. Agertz)

Observations of other spiral galaxies like our own, and of some elliptical galaxies, provide strong evidence for the existence of widespread galactic halos.

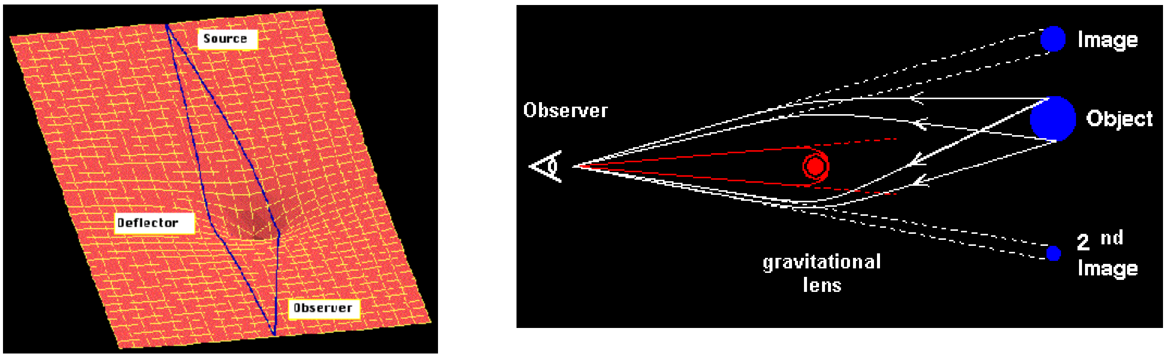
Gravitational lensing

A gravitational lens is formed when the light from a distant object is 'bent' by gravitational forces around a massive object placed between the source and the observer. This effect is predicted in Einstein's General Theory of Relativity. Orest

---

[16] Read, J.I., et al., 2008.

Chwolson first discussed the effect in 1924[17] although it is more usually associated with Einstein's published work in 1926[18].



(a). The deflection of Space-Time by a mass *(b). How a gravitational lens works*

Figure 6 – Gravitational lens; principles of operation

Theory predicts that gravity is produced by massive objects distorting space-time, and that such objects can cause light rays to be deflected, see *Figure 6a*. In such cases, the time taken for the light to reach the observer is altered, causing the image of the source to be distorted and magnified (*Figure 6b*).

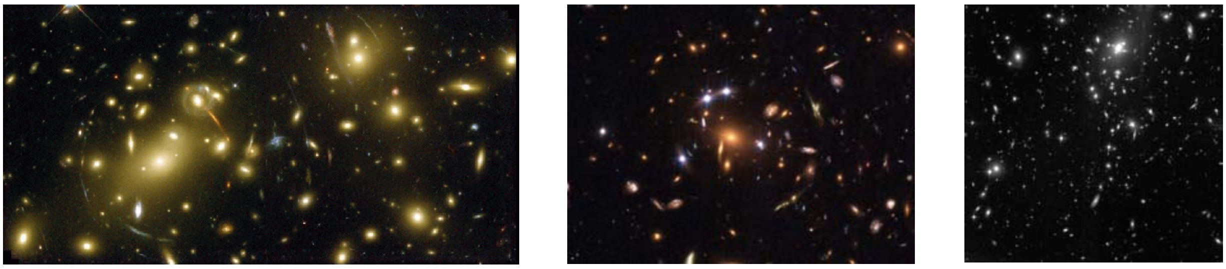
In 1937, Fritz Zwicky[19] suggested that galaxy clusters could act as gravitational lenses, but it was not until 1979[20] that the first observations of the effect were recorded for the quasar QS0957+561 (*Figure 7*). This object was recorded during a search for radio source companions. During the search, two objects showed up with identical redshifts and spectra only 6 arcseconds apart. Initial speculation that this may have been due to gravitational lensing, was confirmed by observations made from Palomar and Mauna Kea Observatories that found a luminous galaxy almost in front of one of the images.

Figure 7 - Composite image of the 'double' quasar QSO 0957+561

Further examples of lensed objects are shown in *Figure 8*. Abell 2218 is a cluster of galaxies about 2 billion light years away - its more distant lensed object lies some 13 billion light years away and is seen at a time only 750 million years after the Big Bang. SDSS J1004+4112 is a multiple imaged quadruple quasar[21]. Abell 1835 IR1916 lies in the constellation of Virgo, has a redshift of z~10.0 [22] and appears to lie at a distance of 13.2 billion light years.

---

[17] Chwolson, O., 1924.
[18] Einstein, A., 1936.
[19] Zwicky, F., 1937.
[20] Walsh, D., et al., 1979.
[21] Williams, L., 2004.
[22] Pelló, R., et al., 2004.



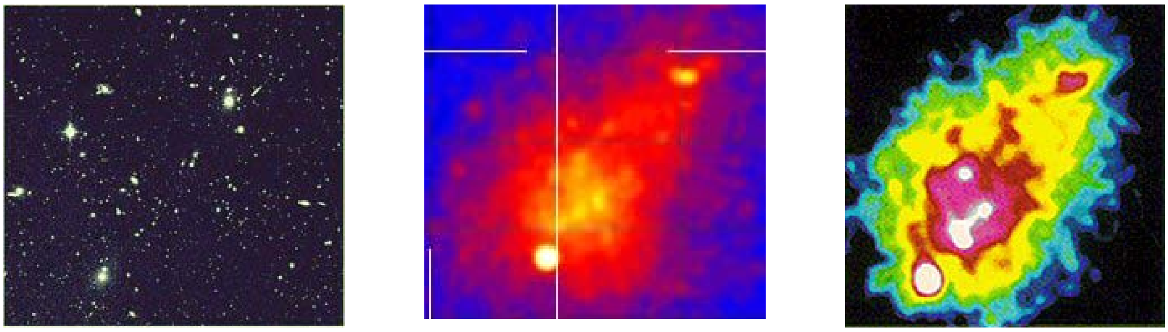
(a). Abell 2218 *(b). SDSS J1004+4112* *(c). Abell 1835 IR1916*

Figure 8 – Galactic lensing effects

Studies of the lensing effects of galaxy clusters suggest that they contain between 10 to 100 times as much dark matters as luminous baryonic matter.

Hot gas in galaxies and clusters of galaxies

Following observations by the Chandra and ROSAT X-ray satellite telescopes, it has been found that clusters of galaxies are intense emitters of X-rays which emanate from very hot plasma gases lying between the galaxies. *Figure 9* shows the Leo Cluster (Abell 1367) in both visible and X-ray, the false colour contour image clearly showing the intensity of the inter-cluster gas.



Optical image of galaxy cluster *ROSAT* X-ray image *False colour contour image*

Figure 9 – Hot gas in the Abell 1367 galaxy cluster (Leo Cluster)

Calculations indicate that there is not enough mass present in the visible components of the cluster to retain its ‘atmosphere’ of gas, suggesting that there is an unseen, dark, component that is gravitationally binding the gases.

The study of hot gas in galaxy clusters suggests that up to 90% of the mass in these systems cannot be seen.

The existence of Dark Galaxies

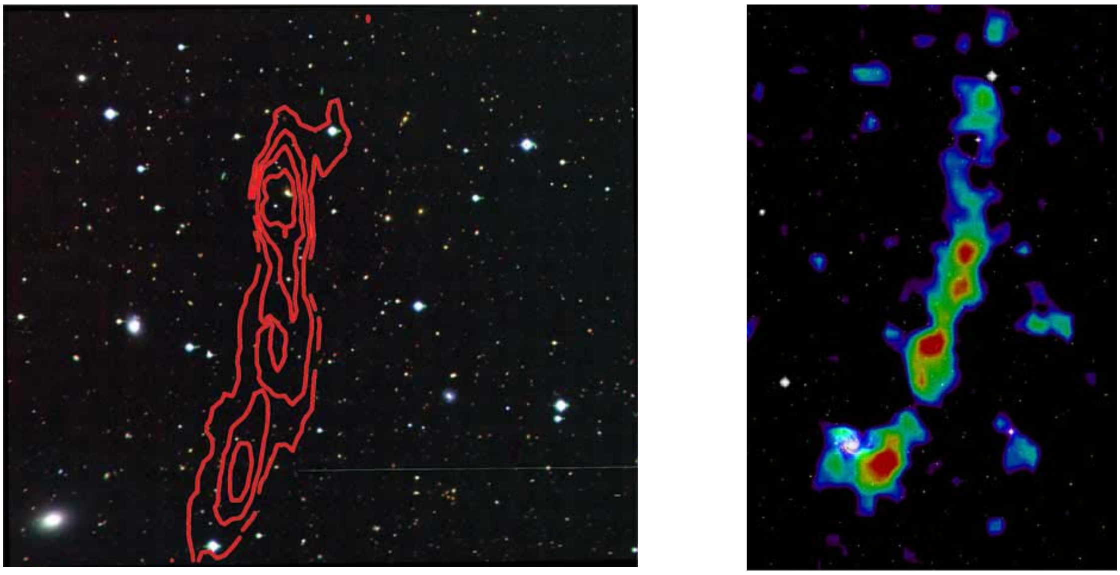
Recent observations suggest that there may be galactic sized objects composed entirely of dark matter.

The object VIRGOHI21 was first noticed in 2000, because of its effect on the nearby galaxy NGC4254. Observations of NGC4254 show that it is lopsided, an effect usually caused by the interaction of a companion galaxy. Optical observations could not find any evidence of a companion, and it was only when radio observations at 21cm[23] were made that the object was found. Radio images revealed a large distribution of hydrogen gas with an equivalent mass of about 100 million suns,

---

[23] Minchin, R,. et al., 2007.

spread over a region of about 50,000 light-years. The gas appears to be circulating around the core of a normal sized galaxy that does not contain any luminous matter. VIRGOHI21 appears to be composed entirely of dark matter and is the first such object to have been found.



(a). The contours superimposed on an optical image indicate the extent of the neutral hydrogen cloud.

(b). Density contours of VIRGOH121 showing the distorted galaxy NGC4254 (visible in the lower left of the image)

Figure 10 – The dark galaxy VIRGOHI21 has no luminous matter.

4. Searching for the Dark Matter component

The weight of evidence suggested by galactic rotation curves, gravitational lensing, cluster dynamics and the detailed analysis of the cosmic background radiation, as well as the results of galaxy distribution surveys suggest that dark matter exists, and that it forms a significant part of the matter distribution in the Universe.

The search for dark matter is taking place on two fronts. One is looking for evidence of non-luminous baryonic matter in the form of massive celestial objects known as MACHOs (MAssive Compact Halo Objects), whilst the other is concentrating on identifying so-far unseen massive non-baryonic sub-atomic particles called WIMPs (Weakly Interacting Massive Particles).

MACHO hunting

This is a generic term for any object made of ordinary baryonic matter (protons and neutrons) that emits little or no radiation. Such objects include black holes, old white dwarfs and neutron stars, feint red dwarfs, brown dwarfs ('failed' stars) and massive freely floating planetary sized objects.

As previously seen, massive galactic bodies can act like a lens and bend light from more distant objects (gravitational lensing). When a small, relatively low mass object causes this it is called microlensing.

The MACHO[24] project in Australia, the EROS (Expérience pour la Recherche d'Objects Sombres)[25] project in Chile and the OGLE (Optical Gravitational Lensing Experiment)[26] investigation, also in Chile have all studied microlensing effects due to MACHOs in our galactic halo. Other projects such as POINT-AGAPE[27] (Andromeda Galaxy Amplified Pixel Experiment) and MEGA (Microlensing Exploration of the Galaxy and Andromeda)[28] have concentrated on extra-galactic events.

Although each of the above studies has focussed on looking for different mass objects in different areas of the sky, they all agree that MACHOs in the range of 10^{-7} to 30 solar masses can only account for roughly 20% of the dark matter mass in our own galactic halo. A value that is infinitesimal on a Universal scale.

Looking for WIMPs

With the failure of baryonic MACHOs to account for the missing mass-energy of the universe, the solution would seem to lie with non-baryonic matter. Several forms of non-baryonic dark matter have been proposed, each classified by a temperature related to the speed of its particles:

***Hot dark matter** (HDM)* – Composed of particles with zero or close to zero mass that can travel (according to the Special Theory of Relativity) at, or close to, the speed of light ($v>0.95c$). The most likely candidate is the neutrino, which is electrically neutral and only interacts through gravity and the weak nuclear force, making it difficult to detect. Neutrinos were created in the early stages of the Big Bang and stopped

---

[24] Kallivayalil, N., et al., 2002.
[25] Beaulieu, J.P., Lamers, H.J.G.L.M. &. de Wit, W.J., 1998.
[26] Udalski, A. et al., 2005.
[27] Calchi Novati, S., 2005.
[28] Crotts, A.,et al., 2000.

interacting with ordinary matter and radiation about one second after the beginning of time.

According to the Standard Model of particle physics, neutrinos have zero mass, and therefore do not contribute to the mass-energy density of the universe. However, a number of experimental projects, including the Super-Kamiokande neutrino observatory[29] in Gifu, Japan, the Sudbury Neutrino Observatory (SNO)[30] in Ontario, Canada and the KamLAND (Kamioka Liquid scintillator Anti-Neutrino Detector) detectors[31] monitoring nuclear reactors in Japan, have concluded that the neutrino does have mass. Theory suggests that there should be between 100 million to 200 million neutrinos per cubic metre of space, providing a predicted neutrino mass of about 0.4 eV/c^2. Whilst this represents a significant mass-energy it only provides about 1% of the mass required.

Warm dark matter *(WDM)* – Consisting of particles such as lightweight primordial neutrinos that move slower than hot dark matter ($v>0.5c$). A study of dark matter halos surrounding dwarf spheroidal galaxies, carried out by a team from Cambridge in 2006[32], concluded that all spheroidal galaxies, regardless of size or luminosity, contained exactly the same amount of dark matter. The volume in which the dark matter halo is contained suggests that the material is moving far quicker than models of cold dark matter propose. If these findings are correct, it suggests the existence of a low-mass, fast moving ('warm') WIMP particle that rarely interacts with ordinary baryonic matter, but which does interact strongly with itself.

Cold dark matter *(CDM)* – Made up of heavy, slow-moving ($v<<c$) particles called WIMPs. These particles only interact through gravity and the weak nuclear force. Since they are not affected electro-magnetically they cannot be seen easily, and because they do not interact with the strong nuclear force they do not react readily with atomic nuclei. In this respect, they respond in a similar fashion to neutrinos, although WIMP particles are theorised to be more massive, thereby slower and colder.

The direct search for WIMPs

Direct detection experiments look for the recoil effects produced when a WIMP particle collides with nuclei of ordinary matter inside a detector. The kinetic energy of the nucleus following such a collision is expected to be very small, in the order of 10^3 to 10^4 eV. This recoil can be detected using four different techniques:

- In semiconductors (such as Silicon and Germanium) and some liquids and gases, electric charge, in the form of electrons, released by the recoiling atom can be collected and measured electronically (`ionization' technique).
- In certain crystals and liquids (known as `scintillators'), flashes of light are produced as the atom slows down. The amount of light produced is dependent on the recoil energy.
- In crystals, the thermal recoil energy is converted into vibrations (`phonons') that can be recorded using cryogenic detectors at very low temperatures (<1 K).
- In gases, the recoiling atoms also produce ionization. This can be collected and measured electronically, or, in some gases, observed as scintillation.

---

[29] Fukuda, S., et al., 2002.
[30] Aharmim, B., et al., 2004.
[31] Araki, T., et al., 2004.
[32] Cleary, D., 2006.

Due to the inherently high background noise produced by natural radioactivity and cosmic rays, detectors are made from exceedingly pure materials and are located deep underground to reduce interference from the cosmic ray muon flux.

The PICASSO and SIMPLE experiments use fluorine in Superheated Droplet Detectors, similar to bubble chambers, to 'listen' for acoustic pulses following the mini-explosion of droplets formed from recoiling fluorine atoms after they have been hit by dark matter particles such as neutralinos.

It is predicted that WIMP recoils should show a seasonal variation due to the fact that the Earth orbits the Sun at about 30 km/s, whilst the Sun itself orbits the galactic centre at about 230 km/s. The two velocity vectors add to give a summer maximum and winter minimum with a predicted annual change in flux in the order of 5%. This phenomenon, known as the WIMP wind[33], should be detectable by directional dark matter experiments such as DAMA and DRIFT.

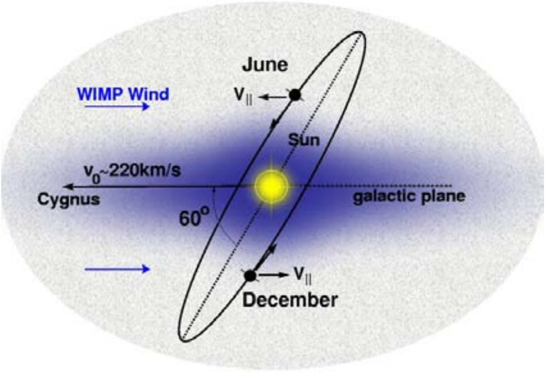


Figure 11 – Diagrammatic representation of the WIMP wind effect.

The DAMA research programme, located in the Gran Sasso Underground Laboratory near Rome, has been operational since 1990. The first DAMA experiment used a sodium-iodide (NaI) scintillator to record photons created by electrons returning to a lower energy state following excitation due to nearby nuclear recoils. Subsequent experiments used liquid Xenon and Germanium detectors for low-background measurements. Early in the year 2000, the DAMA team announced that, over a three year period, they had seen a small (approx 2%) seasonal variation in their WIMP signature.

To date, only the DAMA group have reported an annual variation for low recoil (< 6 keV) energies[34]. These findings remain controversial since other experiments such as the EDELWEISS[35] cryogenic Germanium detector, the ZEPLIN liquid Xenon experiment and the ArDM experiments, using liquid Argon, have been unable to reproduce the results.

Similarly, analysis of the data obtained from the XENON and CRESST experiments located at the Gran Sasso laboratory, the DRIFT ionisation detectors and the NaIAD advanced Sodium-Iodide detectors at the Boulby Mine facility in North Yorkshire, run by the UKDMC (United Kingdom Dark Matter Consortium), and the CDMS experiments in Minnesota have all failed to see WIMP signatures.

---

[33] Tanimori, T., et al., 2004.
[34] Bernabei, R., et al., 2008.
[35] Benoit, A., et al., 2000.

The indirect search for WIMPs

The problems associated with direct searches, i.e. the small number of expected collisions with atomic nuclei and their weak interactions with matter, has led researchers to look for the decay products which should be produced when large numbers of WIMPs collide and destroy each other. It is expected that a collision between two WIMPs should produce energetic gamma-rays (photons), energetic neutrinos or other stable particles such as protons, anti-protons, electrons or positrons.

There have been a number of experiments looking for cosmic antimatter particles (anti-protons and positrons). The BESS high-altitude balloon reported an excess of anti-protons with energies below about 1 GeV, whilst data from the HEAT experiment indicated an excess of positrons with energies greater than 8 GeV. The results from both experiments could be explained through known interstellar nuclear reactions, but they could also be attributed to collisions between dark matter particles such as neutralinos or the theorized Kaluza-Klein multi-dimensional particle. The INTEGRAL satellite launched in 2002 showed a strong 511 keV signal, associated with gamma-rays produced through electron-positron annihilations[36], coming from the galactic centre (*Figure 12*). This may be the result of conventional processes associated with the destruction of matter by the Sgr A* blackhole, but dark matter annihilations could also be a factor.

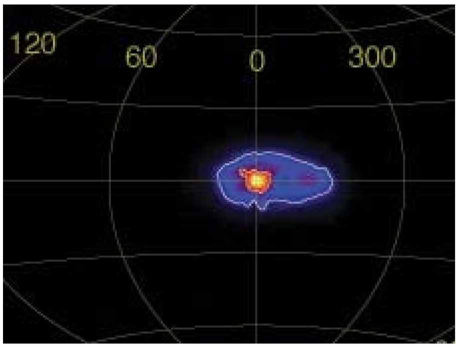


Figure 12 – The 'glow' of 511 keV gamma-rays produced through electron-positron annihilations

Experiments have been designed to look for muon neutrinos produced by the decay of WIMP collision products such as tau leptons, W and Z bosons, quarks and Higgs bosons. Muon neutrinos generated in this way are expected to have energies ranging from a few GeV to a few TeV and their interaction with terrestrial rock produces highly penetrative muons. Experiments use the Earth as a shield against cosmic rays, which may interfere with the results, and have detectors facing the centre of the Earth. Initial experiments produced poor results but a new generation of more sensitive experiments such as ANTARES, AMANDA and IceCube may yield better results.

The search for gamma-ray photons produced through WIMP annihilations uses both ground and space based observations. Ground based detectors called ACTs (Atmospheric Čerenkov Telescopes) search for the faint blue Čerenkov light emitted by high-energy gamma rays as they interact with the atmosphere. Such detectors include VERITAS, HESS, CANGAROO and MAGIC which are typically sensitive to gamma-ray energies in the range of 100 GeV to 10TeV and can distinguish between events caused by gamma-rays and the background 'noise' caused by cosmic rays. Satellite based detectors include EGRET, carried by the Compton Gamma-ray

---

[36] Pospelov, M. & Ritz, A., 2007.

Observatory, and other experiments carried on the INTEGRAL and GLAST satellites. Results from the EGRET experiment indicate possible WIMP annihilations in our galaxies dark matter halo.

In search of hypothetical particles

Amongst WIMP particles, many researchers consider a hypothetical elementary particle called the axion to be the best dark matter candidate. The problem is, that although they are considered to be one of the primary constituents of the universe, none has ever been detected.

Axions are hypothesised to have formed a fraction of a second after time began, during the transition from unified forces to separate electro-weak and strong forces. Having been created at this time they would be ‘cold’, have a zero charge and a mass less than 0.01 eV/c^2. Despite this low mass (less than a hundred billionth the mass of a proton), their abundance could make them a viable CDM candidate. The ADMX (Axion Dark Matter Experiment) survey is searching for weakly interacting axions in the dark matter halo of our galaxy[37] by attempting to convert them into microwave photons using intense magnetic fields. The CAST (CERN Axion Solar Telescope) experiment is also using strong magnetic fields in an attempt to convert solar axions into gamma rays.

Theoretical models suggest a range of other exotic particles, which could meet the requirements of mass and interaction strengths required to account for the necessary amount of cold dark matter. These particles include the neutralino, photino, gravitino, Kaluza-Klein particles, the super-massive Wimpzilla, and a possible fourth type of neutrino, known as the neuterino or sterile neutrino.

---

[37] Duffy, L.D., et al., 2006.

5. Conclusions

To suggest that the Universe is missing mass is a misnomer. The mass is there; it is that, with our present technology, we do not have detectors either of sufficient sensitivity or at the correct frequency to observe it directly. The fact that we cannot see this 'missing' mass has led to it being called 'dark matter'.

Approximately 95% of the Universe is non-luminous, containing a mix of dark matter and another component, dark energy (*Figure 13*). Einstein, in his theory of General Relativity showed that mass and energy are inextricably linked, and it may be that both dark matter and dark energy are manifestations of the same phenomenon.

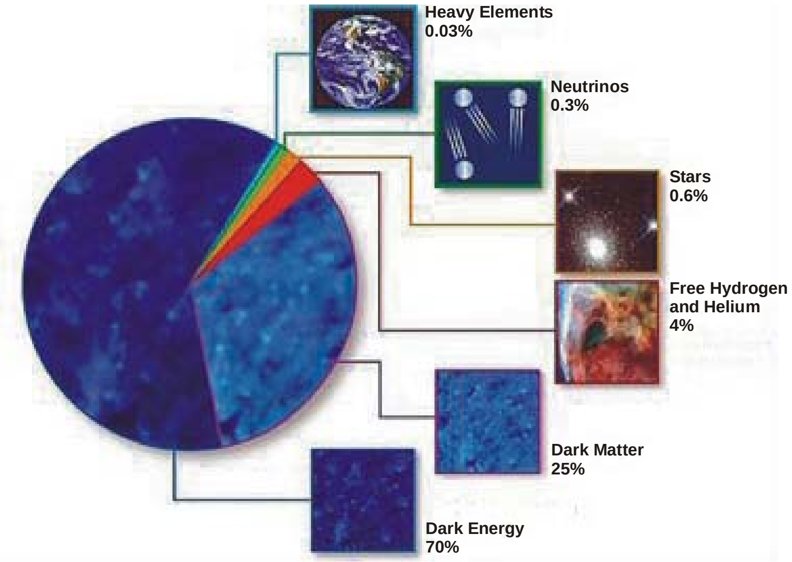


Figure 13 – Matter Distribution in the Universe

The established view is that dark matter is primarily non-baryonic in nature, consisting of one or more elementary particles that are as yet unidentified. The detection of dark matter WIMPs using both direct and indirect methods involves a large scientific community using diverse techniques (see Appendix 1) which, to date, have not produced positive results. Interesting exceptions to this appear to be the findings of the DAMA group and the results of the EGRET experiment.

The existence of dark galaxies, which were fortuitously discovered through the chance gravitational interaction of VIRGOHI21 with NGC4254, indicates that such objects and dark matter itself may lie closer to normal matter than previously thought. The hunt for dark matter continues in all areas. Microlensing studies with more sensitive instruments are due to begin in 2011 with the launch of NASA's SIM (Space Interferometry Mission) and ESA's GAIA (Global Astrometric Interferometer for Astrophysics) missions. New generations of experiments, and the imminent use of the LHC particle-physics accelerator at CERN, are being designed to search for WIMP particle signatures.

With the development of new experiments, and the increasingly overlapping fields of cosmology and particle physics, further research needs to be conducted before the nature of dark matter can be identified with certainty.

March 2009

Appendix 1 – WIMP Experiments

The following list details the experiments mentioned in the text.

Name	Location	Type of experiment
AMANDA (Antarctic Muon And Neutrino Detector Array)		
	Antarctic ice cap.	A neutrino telescope with downward looking detectors, placed at depths of 2500-metres in the ice, looking for Čerenkov light produced by muons created following neutrino interactions with the rock and ice below the detector.
ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch)		
	Mediterranean Sea near Toulouse, France.	A deep underwater neutrino telescope located 2500-metres below the surface with downward looking photomultipliers looking for Čerenkov light emitted by muons created following neutrino interactions in sea water or in the rocks below.
ArDM (Argon Dark Matter Experiment)		
	CERN research facility near Geneva.	Similar to XENON but using liquid Argon detectors. The Argon detectors should be less sensitive to the recoil energy threshold than Xenon.
BESS (Balloon-borne Experiment with a Superconducting Spectrometer)		
	High-altitude balloon flown over Canada and Antarctica.	Designed to detect anti-protons in the cosmic radiation at high altitudes. The central detection device is a magnetic spectrometer that is used to identify all electrically charged particles crossing its main aperture.
CACTUS (Converted Atmospheric Cherenkov Telescope Using Solar-2)		
	Solar Two, Daggett, California, USA.	Ground based ACT using 144 heliostats to form a composite mirror. Flashes of Čerenkov light produced by atmospheric air showers are detected by photomultipliers.
CANGAROO (Collaboration between Australia and Nippon for a GAmma Ray Observatory in the Outback)		
	Woomera, South Australia.	Ground based ACT using a series of large aperture telescopes to study the existence and properties of very high energy gamma rays from celestial objects in the southern sky using Čerenkov technique.
CDMS (Cryogenic Dark Matter Search)		
	Soudan Underground Laboratory in Minnesota, USA.	Using cryogenic silicon and germanium detectors to detect phonons following nuclear recoil events.
CRESST (Cryogenic Rare Event Search with Superconducting Thermometers)		
	Gran Sasso Underground Laboratory, Italy.	An array of cryogenic detectors which can discriminate background radiation events by the simultaneous measurement of phonon and photon signals from scintillating calcium tungstate crystals.
DAMA (Dark MAtter)		
	Gran Sasso Underground Laboratory, Italy.	A direct detection experiment using 9 scintillating thallium-doped sodium iodide (NaI) detectors. Electrons and nuclei recoiling after a collision create photons that are detected using photomultiplier tubes.
DRIFT (Directional Recoil Identification From Tracks)		
	Boulby Mine, N Yorkshire, England.	DRIFT uses low-pressure gas and is the first detector with the capability of measuring the directions of WIMP induced recoils.
EDELWEISS (Experience pour Detecter les Wimps en Site Souterrain)		
	Fréjus underground laboratory, on the Italian-French border.	Using germanium cryogenic detectors to simultaneously measure ionization and heat signals.
EGRET (Energetic Gamma Ray Experiment Telescope)		
	Satellite based ACT.	One of the four scientific instruments on NASA's Compton Gamma Ray Observatory satellite. The experiment was designed to perform an all sky Gamma-ray survey and to detect individual gamma rays with energy from 30 MeV to 30 GeV.

GLAST (Gamma-ray Large Area Space Telescope)		
	Satellite based ACT.	A successor of the Compton Gamma Ray Observatory (CGRO), designed to perform a gamma-ray survey in the 20 Mev to 300 GeV range.
HEAT (High Energy Antimatter Telescope)		
	High altitude balloon.	Designed to detect high-energy primary electrons and their antimatter positrons at energy levels between a few tenths of a GeV to about 50 GeV).
HESS (High Energy Stereoscopic System)		
	Namibia.	HESS is a system of Imaging Atmospheric Čerenkov Telescopes that investigates cosmic gamma rays in the 100 GeV to 100 TeV energy range.
IceCube		
	In the Antarctic ice cap.	A successor to AMANDA, IceCube consists of downward looking detectors placed 2500-metres below the surface ice to look for muons generating Čerenkov light in the ice
INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory)		
	Satellite based ACT.	The INTEGRAL spectrometer is designed to search for gamma-rays resulting from electron-positron annihilations. Its high-purity germanium detectors make precise measurements of the γ-ray energies over the 20 keV to 8 MeV energy range.
MAGIC (Major Atmospheric Gamma Imaging Čerenkov telescope)		
	La Palma, Canary Islands..	Ground based ACT, 17-metre gamma-ray telescope. The MAGIC telescope is the largest Čerenkov detector for gamma ray astrophysics. It is sensitive to photons above energies of 30 GeV.
PICASSO (Project In Canada to Search for Supersymmtric Objects)		
	SNOLAB underground laboratory at Sudbury, Ontario, Canada.	Using a fluorine loaded active C_4F_{10} liquid in the form of droplets. If a fluorine atom recoils following an event a small bubble forms which grows and ‘explodes’. Piezo-electric sensors pick up the acoustic pulse following the explosion.
SIMPLE (Superheated Instrument for Massive ParticLe Experiments)		
	Underground laboratory in Rustrel – Pays d’Apt near Avignon, France.	Similar to the PICASSO SDD experiment but loaded with CF_3I to make the detectors more sensitive to spin-independent events.
VERITAS (Very Energetic Radiation Imaging Telescope Array System)		
	Kitt Peak, Arizona, USA.	A ground-based ACT with an array of four 12-metre optical reflectors for gamma-ray astronomy. It consists of an array of imaging telescopes deployed such that they permit the highest sensitivity in the 50 GeV to 50 TeV band.
XENON		
	Gran Sasso Underground Laboratory, Italy.	A 15 kg liquid xenon detector. The detector simultaneously measures the scintillation and the ionization produced by radiation in pure liquid xenon.
ZEPLIN (Zoned Electroluminescence and Primary Light In Noble Gases)		
	Boulby Mine, N Yorkshire, England.	Located 1100 metres underground. A series of experiments using liquid xenon and photo-multiplier detectors looking for flashes of light produced by recoil events.

For a more comprehensive list of Dark Matter and associated experiments visit: http://www.mpi-hd.mpg.de/hfm/CosmicRay/CosmicRaySites.html

Figure Credits

The following list identifies the sources of the figures used in the text.

Figure.

1. NASA / WMAP team, 2003. COBE-WMAP Comparison. Available at:
   http://www.nasa.gov/centers/goddard/news/topstory/2003/0206mapresults.html
   From: "New image of infant universe reveals era of first stars, age of cosmos, and more".
   [Accessed 22 October 2008].
2. Image: http://www.allamericanpatriots.com/files/images/NASA-coma-galaxy-cluster.jpg
   From: "NASA Astronomy Picture of the Day: Inside the Coma Cluster of Galaxies". Available at:
   http://www.allamericanpatriots.com/photos/nasa-astronomy-picture-day-inside-coma-cluster-gal
   [Accessed 12 October 2008].
3. (a). UK Dark Matter Collaboration, 1997. "Galactic Rotation Curves".
   http://hepwww.rl.ac.uk/ukdmc/dark_matter/rotation_curves.html
   [Accessed 02 November 2008].
   (b). http://odin.physastro.mnsu.edu/~eskridge/astr225/week10.html
   [Accessed 13 December 2008].
4. From: http://en.wikipedia.org/wiki/Bullet_cluster
   [Accessed 18 December 2008].
5. Royal Astronomical Society (RAS) (2008, September 16). "Dark Matter Disk In Our Galaxy, Supercomputer Simulation Shows". ScienceDaily.
   http://www.sciencedaily.com/releases/2008/09/080915210506.htm
   [Accessed 02 November 2008].
6. (a). Cambridge X-Ray Astronomy, 2005. "Clusters of Galaxies: Introduction".
   Available at: http://www-xray.ast.cam.ac.uk/xray_introduction/Clusters_intro.html
   [Accessed 27 October 2008].
   (b). Image adapted from: nrumiano.free.fr/Images/distort1_E.gif.
   From: "The mystery of black holes".
   Available at: nrumiano.free.fr/Estars/b_holes.html
   [Accessed 07 February 2009].
7. From: "Active Galaxies and Quasars – Double Quasar 0957+561".
   Available at: http://www.astr.ua.edu/keel/agn/q0957.html
   [Accessed 04 November 2008].
8. (a). APOD, 2001 October 07. "Abell 2218: A Galaxy Cluster Lens".
   Available at: http://apod.nasa.gov/apod/ap011007.html
   [Accessed 09 November 2008].
   (b). APOD, 2006 May 24. "A Five Quasar Gravitational Lens".
   Available at: http://apod.nasa.gov/apod/ap060524.html
   [Accessed: 09 November 2008].
   (c). Wikipedia, 2008. "Abell 1835 IR1916".
   http://en.wikipedia.org/wiki/Image:Abell_1835_Hubble.jpg
   [Accessed: 09 November 2008].
9. Image: http://www.casca.ca/ecass/issues/1997-DS/West/A1367_hrd.jpg
   From: http://www.casca.ca/ecass/issues/1997-DS/West/west-bil.html
   [Accessed: 31 Dec 08].
10. (a). "New Results confirm Dark Galaxy existence".
    From: www2.naic.edu/~astro/dark_galaxy/
    [Accessed: 31 December 2008].
    (b)."ALFALFA observations of NGC 4254 and the "dark galaxy" VirgoHI21".
    Image: http://egg.astro.cornell.edu/alfalfa/images/n4254color.jpg
    From: http:// egg.astro.cornell.edu/alfalfa/virgohi21.php
    [Accessed 07 February 2009].
11. From: pppa.group.shef.ac.uk/dm/darkMatter.php
    [Accessed: 30 December 2008].
12. From: NASA "Satellite Explains Giant Cloud of Antimatter", 01 September 2008.
    Image: http://www.nasa.gov/images/content/207798main_antimatter_cloud1_226px.jpg
    From: http://www.nasa.gov/topics/universe/features/antimatter_binary.html
    [Accessed: 14 December 2008].
13. Image: http://universe.nasa.gov/press/images/cosmos_percent_comp.jpg
    From: universe.nasa.gov/press/2003.html
    [Accessed: 21 December 2008].

Work Cited in Text

- Aguirre, A., Schaye, J., & Quataert, E., 2001 "Problems for Modified Newtonian Dynamics in Clusters and the Lyα Forest?". *Astrophysical Journal,* **561** pp. 550-558.
- Aharmim, B., et al., 2004. “Electron antineutrino search at the Sudbury Neutrino Observatory”. *Physical Review D*, **70**, 093014.
- Araki, T., et al., 2004. “Measurement of Neutrino Oscillations with KamLAND: Evidence of Spectral Distortion”. *arXiv: Hep-ex/0406035v3. 01 Nov 2004.*
- Beaulieu, J.P., Lamers, H.J.G.L.M. &. de Wit, W.J., 1998. “Some results based on the EROS microlensing survey”. *arXiv: Astro-ph/9811363v2. 08 Dec 1998.*
- Bekenstein, J.D., 2005. “Modified Gravity vs Dark Matter: Relativistc theory for MOND”, *JHEP Conference Proceedings.*
  Available on http://arxiv.orglabs/astro-phy/0412652
  [Accessed 29 October 2008]
- Benoit, A., et al., 2000. “Event Categories in the EDELWEISS WIMP Search Experiment”, *Astrophysics Letters B*, **479**, pp. 8-14. *arXiv:astro-ph/0002462v1. 24 Feb 2000*.
- Bernabei, R., et al., 2008. “First Results from DAMA/LIBRA and the combined results with DAMA/NaI”. *arXiv: 0804.2741v1 [astro-ph] 17 Apr 2008*.
- *Bible.com*. (n.d.). Retrieved October 16, 2008, from http://www.bibleontheweb.com/Bible.asp
- Calchi Novati, S., 2005. “POINT-AGAPE Pixel Lensing Survey of M31: Evidence for a MACHO contribution to Galactic Halos”, *Astron. Astrophys*, **443**, p. 911. *arXiv: Astro-ph/0504188v4. 08 Nov 2005.*
- Caldwell, J.A.R., & Ostriker, J.P., 1981. “The mass distribution within our Galaxy - A three component model”, *Astrophysical Journal, Part 1*, **251**, pp. 61-87.
- Chwolson, O., 1924. "Über eine mögliche Form fiktiver Doppelsterne". *Astronomische Nachrichten,* **221**: p. 329.
- Cleary, D., 2006. “Dwarf Galaxies May Help Define Dark Matter”, *Science, Feb 2006*, **311**, pp. 758-759. DOI: 10.1126/science.311.5762.758b.
- Clowe, D., et al., 2006. “A Direct Empirical Proof of the Existence of Dark Matter”, *Astrophys. J.* **648**, L109 to L113, 2006. *arXiv: Astro-ph/0608407v1. 19 Aug 2006*.
- Cooperstock, F.I. & Tieu, S., 2005. “General Relativity Resolves Galactic Rotation Without Exotic Dark Matter”. *arXiv: Astro-ph/0507619v1. 26 Jul 2005*.
- Crotts, A.,et al., 2000. “Microlensing in M31 - The MEGA Survey’s Prospects and Initial Results”. *arXiv: Astro-ph/0006282v2. 22 Jun 2000*.
- Duffy, L.D., 2006. “A High Resolution Search for Dark-Matter Axions”. *Phys. Rev. D* **74**: 012006.2006. *arXiv:astro-ph/0603108v1 04 Mar 2006.*
- Einstein, A., 1936. "Lens-like Action of a Star by the Deviation of Light in the Gravitational Field". *Science* **84**: pp. 506–507.
- Friedman, A., 1999. "On the Curvature of Space". *General Relativity and Gravitation* **31**, (12), pp. 1991–2000.
- Fukuda, S., et al., 2002. " Search for Neutrinos from Using Super-Kamiokande”. *arXiv:astro-ph/0205304v1 17 May 2002.*
- Hawking, S.W. & Ellis, G.F.R., 1968. "The Cosmic Black-Body Radiation and the Existence of Singularities in our Universe", *Astrophysical Journal,* **152**, pp. 25-36.
- Hawking, S.W. & Penrose, R., 1970. "The Singularities of Gravitational Collapse and Cosmology”, *Proceedings of the Royal Society of London,* series A, **314**, pp. 529-548.
- Hinshaw, G., et al., 2008. "Five-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Data Processing, Sky Maps, and Basic Results". *Astrophysical Journal Supplement (submitted)*.
- Kallivayalil, N., et al., 2006. “Identification of the Microlens in Event MACHO-LMC-20”, *Astrophysical Journal,* **652**, pp. L97-L100. *arXiv: Astro-ph/0609619v1. 21 Sep 2006.*
- Massey, R. et al., 2007. “Dark matter maps reveal cosmic scaffolding”, *Nature*, **445**, pp. 286–290. *arXiv: Astro-ph/0701594v1. 20 Jan 2007.*
- Milgrom, M., 1983. “A Modification of the Newtonian Dynamics as a Possible Alternative to the Hidden Mass Hypothesis”, *Astrophysical Journal,* **270**, pp. 365–370.
- Minchin, R., et al., 2007. “21-cm Synthesis Observations of VIRGOHI 21 – A Possible Dark Galaxy in the Virgo Cluster”. *arXiv: 0706.1586v1 [astro-ph] 11 Jun 2007.*
- Pelló, R., et al., 2004. "ISAAC/VLT observations of a lensed galaxy at z=10.0". *Astronomy & Astrophysics*, **416**, pp. L35-L40.
- Penzias, A.A. & Wilson, R.W., 1965. “A Measurement of Excess Antenna Temperature at 4080 Mc/s”, *Astrophysical Journal*, **142**, pp. 419-421.

- Pospelov, M. & Ritz, A., 2007. “The galactic 511 keV line from electroweak scale WIMPs”. *arXiv: Hep-ph/0703128v1. 12 Mar 2007*.
- Read, J.I., et al., 2008. “Thin, thick and dark discs in ΛCDM”, *Monthly Notices of the Royal Astronomical Society: Letters*, **389** Issue 3, pp. 1041–1057.
- Smoot, G.F., et al., 1992. “Structure in the COBE Differential Microwave Radiometer First-Year Maps”, *Astrophysical Journal,* **396**, pp. L1-L5.
- Tanimori, T., et al., 2004. “Detecting the WIMP-wind via spin-dependent interactions”, *Physics Letters B*, **578**, pp. 241–246.
  Available at: www.sciencedirect.com
- Udalski, A. et al., 2005. “A Jovian-mass Planet in Microlensing Event OGLE-2005-BLG-071”. *arXiv: Astro-ph/0505451v2. 20 Jun 2005*.
- Walsh, D., Carswell, R.F. & Weymann, R.J., 1979. “0957+561-A, B - Twin Quasistellar Objects or Gravitational Lens” *Nature* **279**, pp. 381–384.
- Williams, L., 2004. “Models of the Giant Quadruple Quasar SDSS J1004+4112”, *The Astronomical Journal*, **128**, pp. 2631–2641.
- Worsley, A., 2008. “An advanced dynamic adaptation of Newtonian equations of gravity”, *Physics Essays,* **21**: (3), pp. 222-228 (2008).
- Zwicky, F., 1933. “Die Rotverschiebung von Extragalaktischen Nebeln,” *Helvetica Physica Act*a, **6**, pp. 110–127.
- Zwicky, F., 1937. "Nebulae as Gravitational Lenses", *Physical Review*, **51**(4), p. 290.

Other References used

- Allday, J., 2002. *Quarks, Leptons and the Big Bang*. 2nd ed. Abingdon: Taylor & Francis. ISBN: 0 7503 0806 0.
- Alpher, R.A., Bethe, H.A. & Gamow, G., 1948. “The Origin of Chemical Elements”, *Physical Review,* **73**, pp. 803-804.
- Ananthaswamy, A., 2008. South Pole Dreamcather. *NewScientist*, 19 Apr 2008, 198 (2652), pp. 34-37.
- Balbi, A., 2008. *The Music of the Big Bang: The Cosmic Microwave Background and the New Cosmology*. New York: Springer. ISBN: 978 3 540 78726 6.
- Bennett, C.L., et al., 2003. “The Microwave Anisotropy Probe Mission”, *Astrophysical Journal,* **583**, pp. 1-23.
- Clowe, D. & Zaritsky, D., 2007. “Shot in the dark”, *Physics World, Feb 2007*, pp. 26-29.
- Cornell, J. ed., 1995. *Bubbles, voids and bumps in time: the new cosmology*. Cambridge University Press. ISBN: 0 521 42673 1.
- Einstein, A., 2007. *Relativity: The Special and General Theory*. East Bridgewater: Signature Press Editions. ISBN: 1 57215 469 1.
- Frenk, C.S. et al., 1988. “The Formation of Dark Halos in a Universe Dominated by Cold Dark Matter”, *The Astrophysical journal*, **327**, pp 507-525.
- Gao, L. & Theuns, T., 2007. “Lighting the Universe with Filaments”. *Science, 14 Sep 2007,* **317**: pp. 1527-1530. *arXiv: 0709.2165v1 [astro-ph] 13 Sep 2007*.
- Guth, A.H., 1981. "The Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems", *Phys. Rev. D* **23**, pp. 347-356.
- Guth, A.H., 1997. *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins*. Perseus. ISBN 0-201-32840-2.
- Hawley, J.F., & Holcomb, K.A., 2006. *Foundations of Modern Cosmology*. 2nd ed. Oxford: Oxford University Press. ISBN: 0 19 853096 X.
- Muir, H. ed., 2008. Has dark matter been detected? *Sky at Night*. Jun 2008, p. 16.
- Nicholson, I., 2007. *Dark Side of the Universe: Dark Matter, Dark Energy, and the Fate of the Cosmos*. Bristol: Canopus Publishing Ltd. ISBN: 0 95498463 3.
- Panek, R., 2008. The Quest for dark Matter. *Sky & Telescope*, Aug 2008, 116 (2), pp. 30-35.
- Perkins, D.H., 2006. *Particle Astrophysics*. Oxford: Oxford University Press. ISBN: 0 19 850952 9.
- Seymour, P., 2008. *Dark Matters: Unifying Matter, Dark Matter, Dark Energy and the Universal Grid*. Franklin Lakes: The Career Press. ISBN: 9 781601 630063.
- Smid, T., 2008. “The Dark Matter Myth: Magnetic Fields and Galactic Rotation Curves”.
  Available on http://www.physicsmyths.org.uk/darkmatter.htm
  [Accessed 28 October 2008].
- Viel, M., et al., 2006. “Can Sterile Neutrinos Be Ruled Out as Warm Dark Matter Candidates?”. *arXiv: Astro-ph/0605706v2. 05 Sep 2006*.
- Villard, R., 2004. Unveiling the Dark Universe. *Astronomy*. *(Origin & Fate of the Universe, Special Edition)*. Nov 2004.
- Waller, W.H. & Hodge, P.W., 2003. *Galaxies and the Cosmic Frontier*. London: Harvard University Press. ISBN: 0 674 01079 5.
- Wikipedia, 2008. *Axion* [Online] (Updated 30 January 2009)
  Available at: http://en.wikipedia.org/wiki/Axion
  [Accessed 02 February 2009].
- Wikipedia, 2008. *Black body* [Online] (Updated 21 October 2008)
  Available at: http://en.wikipedia.org/wiki/Black_body
  [Accessed 21 October 2008].
- Wikipedia, 2008. *CERN Axion Solar Telescope* [Online] (Updated 13 June 2008)
  Available at: http://en.wikipedia.org/wiki/CERN_Axion_Solar_Telescope
  [Accessed 02 February 2009].
- Wikipedia, 2008. *Friedmann equations* [Online] (Updated 03 January 2009)
  Available at: http://en.wikipedia.org/wiki/Friedmann_equations
  [Accessed 05 January 2009].
- Zacek, V., 2007. Dark Matter. *Proceedings of the 2007 Lake Louise Winter Institute. Mar 2007. arXiv: 0707.0472v1 [Astro-ph 03 Jul 2007]*.
- Zwicky, F., 1937. "On the Masses of Nebulae and of Clusters of Nebulae", *The Astronomical Journal*, **86**(3), pp. 217–246.