Dark Matter

The idea of Dark Matter has been in the press for about a decade and yet there is still little known about this phenomenon. The term 'Dark Matter' was first used by Fritz Zwicky (1898-1974) in 1933. There have been many theories proposed that could explain this strange phenomenon but in the past decade it has been beyond astrophysicists to accurately describe what dark matter is.

The fact that matter will emit radiation in one form or the other is used by astronomers to see if there is matter in any given system, although this can not be always relied on as planets like the Earth do not emit enough radiation for them to be observed at long distances[1]. This was not a major problem as the Sun accounts for 99% of the mass in our Solar System, the assumption was so made that most of the Universe's mass would be luminous (the majority of the Universe's mass being contained within stellar objects like the Sun).

The first observation that indicated that there was more mass in the Universe that could not be readily 'seen' was by Zwicky who in 1933 from observations of eight galaxies in the Coma Cluster found that the radial velocities of these galaxies were extraordinarily high ($V = 1019 \pm 360\ kms^{-1}$). This meant that the light-to-mass ratio of the Coma Cluster would have indicated a mean density 400 times great than that derived from that of the luminous matter. In Zwicky's case he had over-estimated what the light-to-mass ratio was due to the Hubble Constant being incorrect[2]. With use of the modern value for the radial velocity would be $400 \pm 50\ kms^{-1}$. From this evidence he came up with the theory that there was non-luminous dark matter accounting for the mass difference. The idea that there may be dark matter was further verified by Smith in 1936 who was taking observations of the Virgo Cluster, which also appears to have an unexpected high mass.

The evidence for dark matters existence was increasing and further stronger evidence came in the 1970s when various scientists decided to measure rotation curves for spiral galaxies. For a long time it had been known that galaxies will spin around their centre of mass. So this will mean that will follow Kepler's Laws for orbits around a centre:

$$V_c = \sqrt{\frac{GM}{r}} = \text{Circular Velocity} \qquad (1)$$

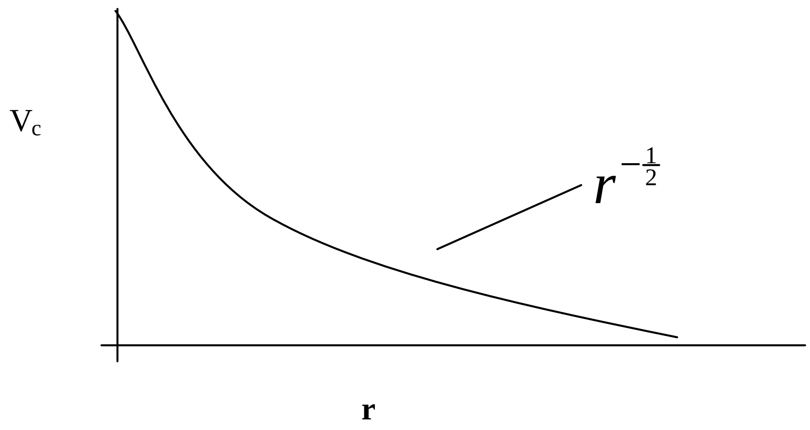
(V_c - centripetal velocity, G - Newton's Gravitational Constant - 6.67×10^{-11}, M – mass of the system, r – distance from centre of mass of the point).

This comes from equating the centripetal force to the force given by Newton's Law of Gravitation for an object orbiting around the centre of mass. Kepler's Laws state that the rotational velocity around the centre only depends on the distance to the centre

[1] Planets like Jupiter do, this is how evidence can be found for extra solar planets.
[2] From evidence at the time the value was as accurate as could be but over the past century the accuracy of this value has been increased and the Hubble Constant is approximately 75 kms^{-1}Mpc.

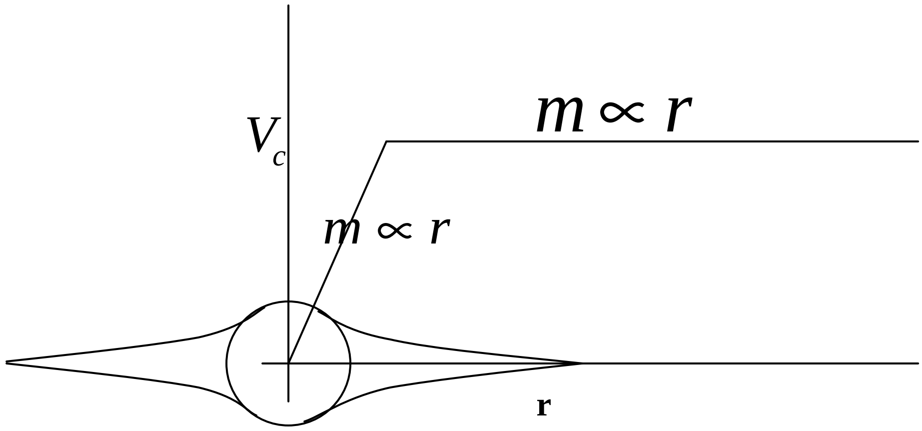
and the total mass of the system is contained within the orbit. So if the rotational velocities along a galaxy could be found then it would be possible to find out the mass of the galaxy inside the orbit of the point concerned.

Figure 1

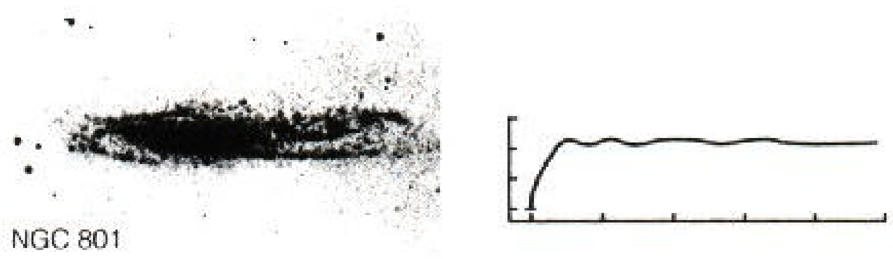


So as you go away from the centre of the galaxy the velocity of the matter orbiting the point will decrease like in Figure 1[3]. The evidence in this method for dark matter comes from the fact that as you go along the edge of a galaxy the luminosity of the galaxy decreases and so it was thought that so does the mass and therefore the rotational velocities. The fact that the rotational velocities do not decrease would indicate the fact that there is more mass there, matter that can not be detected by conventional means since it does not radiate. This is the first and strongest evidence for dark matter within galaxies.

Figure 2



[3] Of course this is making the assumption that most of the matter of the galaxy is contained in its most luminous point which is at the centre of the galaxy.



[4]

Initially the body behaves like a solid disk; the velocity increases linearly with radius[5]. However there is no Keplerian decline, since there is no fall off, therefore this means the end of the galaxy can not be detected. So galaxies are much larger than we thought from just there 'visible'[6] mass, these halos of dark matter around the galaxies are huge. The optical size is of a galaxy is approximately 10Kpc, and as there is no fall off after much larger distances so they must be larger than they look.

Since there is so much overwhelming evidence that dark matter does exist, what could it be? There are lots of theories in this area, some of which have now been almost discounted but not quite forgotten, because as with most things in physics no theory is without its problems - especially when it comes to such theoretical concepts. The observations do not indicate which of the current theories are correct but some seem more likely to be correct than others. The ones that have been discounted are not totally removed from the mind as one aspect of the theory may be useful.

Currently the most favoured theory is the cold dark matter (CDM) theory; in this there are particles moving at low velocities (and a low energy, producing the idea of cold dark matter) which will make it easier for the gravity to pull them together to form galaxies. A very strong indication that this model is correct would come from large galaxies such as the Milky Way having numerous dwarf galaxies orbiting them. There have however been no small satellite galaxies found around, this failure to find the predicted dwarf galaxies has led scientists to call for the abandonment of this model of dark matter.

There is also the opposite in name, the hot dark matter theory (HDM). This theory is older and has almost now been ruled out. The hot dark matter theory is primarily 'represented' by neutrinos[7]; in this case it does not account for the pattern of galaxies which have been observed in the Universe. Neutrinos would have emerged from the Big Bang with high relativistic velocities and so they would tend to smooth out any fluctuations in the matter density of the Universe. In the early Universe, the neutrino density is thought to have been enormous, so most of this matter density could easily be accounted for by neutrinos. At these velocities the neutrinos would tend to move out of any regions with densities greater than the average. So by this process the fluctuations in the density of matter would have appeared only after the neutrinos had slowed down by a large factor. Evidence that has discounted this theory was found by the COBE[8] satellite - the neutrino dominated Universe would not have enough power

[4] The image of NGC 801 and its corresponding plot of Velocity against radius are from University of California, San Diego Centre for Astrophysics & Space Sciences Website.
[5] Velocity is proportional to the radius
[6] This includes all wavelengths of the Electromagnetic Spectrum that can be detected.
[7] These are particles with little or no mass and do not interact strongly with matter.
[8] Cosmic Background Explorer, launched by NASA.

to count for the observations made. This means that the hot dark matter theory is a poor model and on its only could not support observations.

Another form of the cold dark matter theory is WIMPs theory - WIMPs being Weakly Interacting Massive Particles. WIMPs are consistent with the Big Bang theory. They are exotic subatomic particles and have been given names such as axions, massive neutrinos, and photinos. These particles would have mass of perhaps 10 to 100 times that of a proton[9] and therefore could account for a large proportion of the dark matter, assuming as predicted that they are common. These particles would move much slower than light because of their relatively high mass. They do not interact with radiation and so they would not affect the uniformity of the cosmic background radiation. If they do exist they could have been the 'seeds' around which the ordinary matter came to form galaxies. The only problem is there never has been a particle of this type observed so it is unlikely that this is the solution to the problem of what dark matter is.

A type of dark matter that has not been fully discounted are MACHOs - Massive Compact Halo Objects these could exist in large numbers in the vast halos that surround galaxies. Examples that have been put forward are brown dwarfs[10], white dwarfs[11], black holes and neutron stars[12].

Some objects have been found to be either brown dwarf stars or very large planets orbiting around stars. Observations of the brightening and dimming of distant stars[13] is evidence for a large population of brown dwarfs, however this population still would not be enough to account for the dark matter in our galaxy.

White dwarfs have been found in large numbers and could be plentiful enough to explain the dark matter, but for this to happen the young galaxies which produce white dwarfs must produce white dwarfs which cool more rapidly than present theories predict. The problem is that the production of large numbers of white dwarfs implies that there would be a large amount of helium produced, which is not observed.

In the case of black holes and neutron stars they can be dark, especially black holes, which do not emit any visible radiation. This would mean that they would quite easily fit in with one of the properties of dark matter - their being dark. These however are unlikely to be the source of dark matter as the processes which form these objects release a lot of energy and heavy elements, and there is no evidence for this sort of release. They are also expected to be much scarcer than white dwarfs.

There is one last case that is probably quite extreme but can not be discounted as a possibility. This is the case that we do not understand the process of gravity very well. Perhaps at large scales gravity does not work the same as gravity does on the small scales which we can measure.

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[9] The rest mass of a Proton is 1.672×10^{-27}kg.

[10] Stars that have a mass less than eight percent of the mass of the Sun, this mass is too low to produce the nuclear reactions that make stars shine.

[11] These are the final condensed states of small to medium sized stars.

[12] These are the final condensed states of large and very large stars.

[13] This is thought to be due to the gravitational lens effect of a foreground star.

There is no definite explanation to what dark matter is. The cold dark matter and hot dark matter theories both have their own problems. Hot dark matter can not form small structures like galaxies and cold dark matter can not form larger scale structures such as clusters[14] and super-clusters[15]. The universe is structured; galaxies are not in random patterns but form clusters and super-clusters which have empty voids in between them. Perhaps a theory which puts both the hot dark matter and cold dark matter theories together, a mixed dark matter theory, could be the solution to the question of what dark matter is. Whatever dark matter is, we know that it is the dominant source of gravitation forces in Universe with some 90%[16] of the Universe being made up of dark matter, and until we can say what this dark matter is we will not necessarily understand the process of gravitation fully.

[14] These are groups of galaxies that are all connected.
[15] These are groups of clusters which form larger structures.
[16] This value is dependant on the value of O which is the critical density of the Universe.

References:

The Early History of Dark Matter, SIDNEY VAN DEN BERGH
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Image: University of California, San Diego, Center for Astrophysics & Space Sciences (**casswww.ucsd.edu/public/ tutorial/DM.html)**