Essay

DARK MATTER

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Abstract

Many observations - the rotational curves of the spiral galaxies, x-ray halos of the elliptical galaxies, virial theorem applied to the groups of galaxies, x-ray emitting hot gas contours in the clusters of galaxies and most recently the evidence from the gravitational lensing suggest that there is at least 90% matter in the Universe shows its presence through its gravitational effects only.This component of matter is called the Dark Matter.I have discussed the various observational evidence which hint at Dark Matter in this essay.Also, I have discussed the various candidates for the Dark Matter - the non-baryonic being the dominant one.

1 Introduction

Virtually all of the information we have about the Universe has come to us through photons : optical photons from stars, radio photons from neutral hydrogen gas, X-ray photons from ionized gas, and so forth. Yet there is no reason to suppose that every type of matter in the Universe emits a train of readily detected photons .For example, we know of no reason why the star-formation process should not produce stars with masses below the lower limit for hydrogen burning on the main-sequence($.08M_{\odot}$), and any such stars would have to be very nearby $(\ll 1pc)$ to be detectable with our present instruments. Neutral hydrogen gas in interstellar space would be far more difficult to detect if there were no 21-cm hyperfine transition. Dust in galaxies was discovered only because dust grains happen to be small compared to optical wavelengths.

Even with a given type of astronomical object, there is no *a priori* reason why mass and luminosity ought to be well correlated.This point is illustrated by the main-sequence luminosity function in the solar neighborhood.Stars brighter than the sun contribute 95% of the luminosity while the stars fainter than the Sun contain at least 75% of the mass. Hence even modest variations in the relative numbers of low-mass and high-mass stars can produce substantial changes in the overall mass-to-light ratio **Q**.Neverthless, the mass-to-light ratios in the well-studied central parts of many different spiral and elliptical galaxies somehow contrive to be roughly the same. This similarity leads naturally to the conjecture that mass-to-light ratios of this order also apply to the regions of smaller luminosity density, such as the outer parts of individual galaxies, or clusters of galaxies. I have shown in this essay how this extrapolation has proved to be wrong.I have shown that how it is seen that on large scales, most astronomical systems have much larger mass-to-light ratios than the central parts of galaxies.Moreover, the volume of these regions of high mass-to-light ratio is so great that they contain over 90% mass of the Universe.

What is the reason for these unexpectedly high mass-to-light ratios?Could it be that in low-density regions the star-formation process produces predominantly low-mass objects, such as faint *M* dwarfs or even planetary-sized objects? Could there be a vast population of black holes and neutron stars that are remnants of a generation of primordial stars? Or is the most of the mass of the Universe tied up in some exotic elementary particle ? These are the questions which I have addressed in this essay.

The first step toward answering these questions is to examine critically the *minimum* mass-to-light ratios that are compatible with our current understanding of stars and galaxies.I have begun in section 2.1 with the environment for which we have the fullest information, the solar neighborhood.

The term dark matter is used to denote *any form of matter whose existence is inferred solely from its gravitational effects.* For example, the white dwarfs in the solar neighborhood are not considered to be dark matter, even though most of them have cooled to invisibility, since their existence is inferred directly from the present density of visible white dwarfs and main-sequence stars, the theory of stellar evolution, and an estimate of the history of the star-formation rate in the solar neighborhood.

The first evidence of dark matter was found by Swiss astronomer Fritz Zwicky in 1933.His work was based on the measurements of the radial velocities of seven galaxies belonging to the Coma cluster of galaxies.He pointed out that the individual galaxies had radial velocities that differed from the mean velocity of the cluster, with an RMS dispersion of about 700 km/s. He interpreted this dispersion as a measure of the kinetic energy per unit mass of the galaxies in the cluster, and by making a crude estimate of the cluster radius he was able to measure the total mass of the cluster using the virial theorem.

Zwicky's next step was to compare the cluster mass-to-light ratio measured in this way with the mass-to-light ratio as measured from the rotation curves of nearby spirals.He found that that the cluster mass-to-light ratio exceeded the rotation curve mass-to-light ratio by a factor of least 400. He concluded that virtually all of the cluster mass is in the form of some invisible or dark matter that is undetectable except through its gravitational force.

Then,Ostriker et al.(1974) and Einasto et al. (1974) have proposed that there are large amounts of dark matter even around isolated galaxies: they argue that the dark matter in spiral galaxies is located in giant ”halos” extending to several times the radius of the luminous matter and containing most of the total galaxy mass.It is possible that the dark matter in halos is the same as the dark matter in clusters like the Coma cluster, except that in clusters the galaxies are so closely packed that the dark matter resides in a common background rather than in separate halos.

2 Dark Matter in Individual Galaxies

2.1 The Solar Neighborhood

The local mass density in main-sequence and giant stars, stellar remnants(both directly observed and inferred from models of galactic evolution), gas, and duct yields a lower limit to the total density $\rho_{min} \simeq 0.11 M_{\odot} pc^{-3}$, while the luminosity density in the V band is $j_V \simeq 0.067 L_{\odot} pc^{-3}$.Thus in the galactic mid-plane

$$Q_{min}(local, z = 0) = \frac{\rho_{min}}{j_V} \simeq 1.7 Q_{\odot}. \quad (1)$$

Surface density and surface brightness in a column perpendicular to the plane are more fundamental quantities than volume density or luminosity density, since different stellar populations have different thicknesses .The surface density in known components is $50 M_{\odot} pc^{-2}$ and the surface brightness is $15 L_{\odot} pc^{-2}$ in V. Almost all the light comes from the heights < 700 pc above the mid-plane. Thus

$$Q_{min}(local, |z| < 700pc) = 3.3 Q_{\odot}. \quad (2)$$

This is the minimum mass-to-light ratio in a typical Population I system.

To estimate the mass-to-light that is due to the total gravitating mass in the solar neighborhood , we use the model of our galaxy based on the collisionless Boltzmann equation.We use the relation between the gravitational force $\mathbf{F}$ and the mass density ρ arising from the Poisson equation : $\nabla.\mathbf{F} = -4\pi G\rho$. Assuming that the galaxy is axisymmetric and using a cylindrical coordinate system (R, ϕ, z), we can write this equation in the form

$$\rho = -\frac{1}{4\pi G}\left(\frac{\partial F_z}{\partial z} - \frac{1}{R}\frac{\partial v_c^2}{\partial R}\right), \quad (3)$$

where we have used the fact that $F_R = -(v_c^2/R)$. Observationally, v_c is approximately independent of R and the second term in the parentheses does not vary much with z for $z \ll R$. Hence we can integrate eq. (3) along the z axis to obtain the surface mass density:

$$\Sigma(R,z) \equiv 2\int_0^{z'} \rho(R,z') \simeq -\frac{1}{2\pi G}[F_z(R,z) - \frac{z}{R}\frac{\partial v_c^2}{\partial R}]. \tag{4}$$

We have assumed that the galaxy is symmetric about $z = 0$ plane so that $F_z(R,0) = 0$. To determine F_z we select a population of stars and determine their random velocities σ_z along the z direction and their number density n along the z axis. We can then determine F_z from the Jeans equation,

$$nF_z = \frac{\partial n\sigma_z^2}{\partial z} + \frac{1}{R}\frac{\partial}{\partial R}(Rn\sigma_R^2 z), \sigma_{ij}^2 \equiv < v_i v_j >, \tag{5}$$

provided the second term can be ignored.

if we can measure n and ¡v_z^2¿ as functions of z, then this equation can be used in eq. (3) to estimate mass density ρ .More elaborate statistical techniques leads to the estimates $\rho \equiv 0.18 \pm 0.03 M_\odot pc^{-3}$ and $\Sigma(700pc) \simeq 75 M_\odot pc^{-2}$. Because the luminosity density (near the sun) is $\sim 0.067 L_\odot pc^{-3}$, we get the mass-to-light ratio as

$$Q = 2.7 Q_\odot \tag{6}$$

. Similarly, using the fact that the surface brightness is $\sim 15 L_\odot pc^{-2}$, we find the integrated mass-to-light ratio to be $\sim 5Q_\odot$. Both these values exceed the corresponding mass-to-light ratios, based on luminous matter, by $\sim 50\%$. Thus nearly one-third of the material in the solar neighborhood must be considered dark matter.

2.2 Dark Matter in Milky Way

The existence of dark matter near the Sun raises the following question: How far does the dark-matter halo extend? A rough estimate can be made as follows: Let us assume that the rotational velocity of our galaxy has a constant value V_0 up to a radius $r = L$ and falls as $r^{-\frac{1}{2}}$ beyond L. This is equivalent to assuming that the mass distribution of the halo is given by

$$M(r) = \begin{cases} (V_0^2 r/G) & \text{if } r < L \\ M_0 & \text{if } r > L \end{cases} \tag{7}$$

Corresponding to this mass distribution, we get the gravitational potential ϕ:

$$\phi(r) = \begin{cases} (V_0^2[ln(r/L) - 1] & \text{if } r < L \\ -(V_0^2 L/r) & \text{if } r > L \end{cases} \tag{8}$$

All the stars in the solar neighborhood with speeds significantly higher than the escape velocity in this potential would have escaped by now. So the maximum stellar velocity v_{max} we expect in solar neighborhood will be given by the condition

$$\frac{1}{2}v_{max}^2 + \phi(R_0) < 0. \tag{9}$$

Observations in the solar neighborhood suggest that the velocity distribution of stars shows a sharp cutoff around $v_{max} = 500km/s$ into Eq.(8), we find that $L > 4.9R_0$. Or, because $R_0 \simeq 8.5kpc$, $L > 41kpc$, corresponding to a total mass of $M_0 > 4.6x10^{11}M_\odot$.Because the total luminosity of our galaxy is $L_{total} \simeq 1.4x10^{10}L_\odot$, the mass-to-light ratio for our galaxy is bounded by the inequality $Q > 33Q_\odot$.This value is at least six times larger than the value in the solar neighborhood, suggesting that Q increases with the increasing scale.

An independent estimate of the extent of our galactic halo can be made with the Magellanic clouds and the dynamics of the satellite galaxies that are gravitationally bound to the Milky Way. These procedures lead to larger values of L, in the range of 50-80 Kpc.

2.3 Rotation Curves of the Spiral Galaxies

The rotation curve provides the most direct method of measuring the mass distribution of a galaxy.The rotational curve is the plot of the rotational velocity of a galaxy at various distances from the center of rotation vs the distance from the center of rotation.

In a spiral galaxy the gas, dust and stars in the disk of the galaxy are all in orbit around a common center.The gravitational attraction due to the mass $M(r)$ lying between the center and an object of mass m in an equatorial orbit at a distance r from the center is given by Newton's law GmM_r/r^2.It equals $mv(r)^2/r$, where v(r) is the orbital velocity.

Rotation curves can be measured optically from emission lines in HII regions, or at radio wavelengths using the 21-cm emission line of neutral hydrogen.Neutral hydrogen observations generally extend to larger radii.

The rotation of the galaxy will carry the stars and gas on one side of the galactic nuclei toward our galaxy and those on the other side away from it.The spectral lines of the approaching material will therefore be blue-shifted, and lines of the receding material will be red-shifted.A measurement at any point on a spectral line will therefore provide the velocity along the line of sight at that distance.

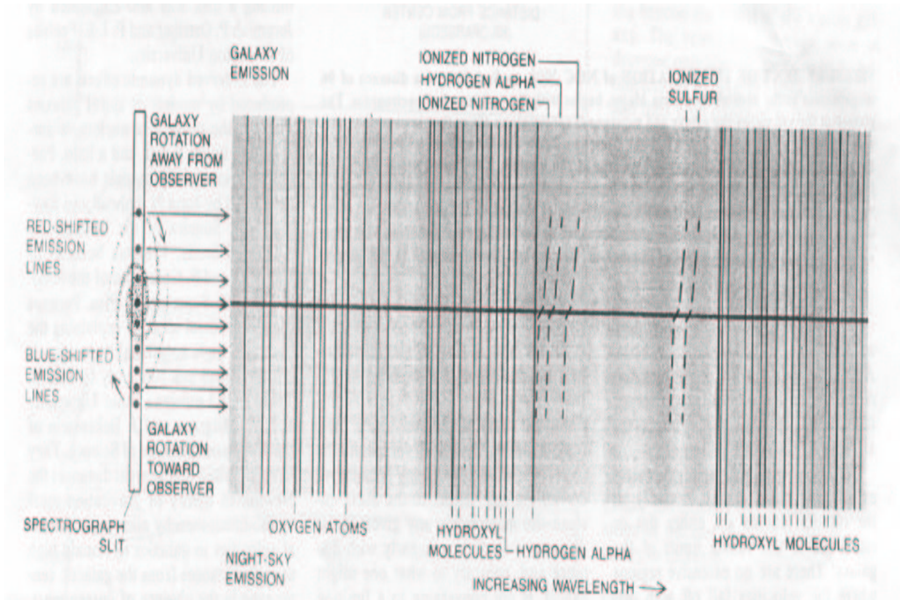

Figure 1: EMISSION LINES in the spectrogram of NGC 7541

The early optical measurements were usually restricted to the inner parts of galaxies.These curves typically showed a steep rise in the rotation speed near the center, then a short level section before the last data point was reached.This behavior is characteristic of the exponential disk which can be divided into three regions : (1) an inner region in which the speed rises linearly with distance from the center; (2) a region where the speed reaches a maximum and then begins to decline (at the **turnover radius**); and (3) a **Keplerian region** in which the potential of the disk resembles a point mass potential, so that the rotation speed falls as $R^{-1/2}$.Observers identified the location of the level section in their rotation curves with the turnover radius and to assume a Keplerian falloff in rotation speed past the last measured point.

The situation changed around 1970, as improved sensitivity in both optical and 21-cm observations permitted rotation curves to be extended to larger radii. these observations began to show that the flat portion of the rotation curve extended further than an exponential disk model would predict, and there was no sign of a Keplerian falloff.The conclusion is that mass, unlike luminosity, is not concentrated near the center of spiral galaxies.Thus the light distribution in a galaxy is not at all a guide to mass distribution.There is no well-established example of a

Keplerian region in any galaxy rotation curve. So, *there is no spiral galaxy with a well-determined total mass*.

The simplest interpretation of these results is that the spiral galaxies possess massive dark halos that extend to larger radii than the optical disks.If we approximate the dark halo as spherical, and are at sufficiently large radii that the gravitational force from the disk can be neglected, then a rotation curve with constant velocity implies that that the halo mass increases linearly with radius out to a radius beyond the last measured point.the corresponding dark halo density is

$$\rho(r) = \frac{1}{4\pi r^2}\frac{dM(r)}{dr} = \frac{v(r)^2}{4\pi G r^2} \tag{10}$$

The dark halo density must fall below the value given by above Eq. at small radii, since the observed rotation rotation curves remain flat even when the disk mass contributes a substantial fraction of the rotation speed. A better parameterization of the halo density is therefore given by the fitting formula

$$\rho(r) = \frac{\rho_0}{1+(r/a)^\gamma} \tag{11}$$

If both a rotation curve and accurate photometry are available, then the mass-to-light ratio of the disk and the halo parameters $\rho_0, a,$ and γcan all be fitted simultaneously.

2.4 Dark Matter in the Elliptical Galaxies

(a) Isothermal sphere fitting

The cores of the galaxies can be modeled theoretically by an isothermal sphere.With such a theoretical model, we can estimate the amount of dark matter in these systems.

The isothermal sphere is parameterized by two variables: the velocity dispersion σ^2 and the central density ρ_0.we can define a core radius $r_0 = (9\sigma^2/4\pi G\rho_0)^2$.To determine the mass-to-light ratio for such a system - say, the core of an elliptical galaxy - we proceed as follows: The observed luminosity profile of the elliptical core is fitted to an isothermal sphere, allowing us to determine the best-fit values for r_0 and central brightness I_0.The central emissivity is therefore $j_0 \simeq (I_0/2r_0)$.Thus the central mass-to-density ratio is

$$Q = \frac{M}{L} = \frac{\rho_0}{j_0} = \frac{9\sigma^2}{2\pi G I_0 r_0}. \tag{12}$$

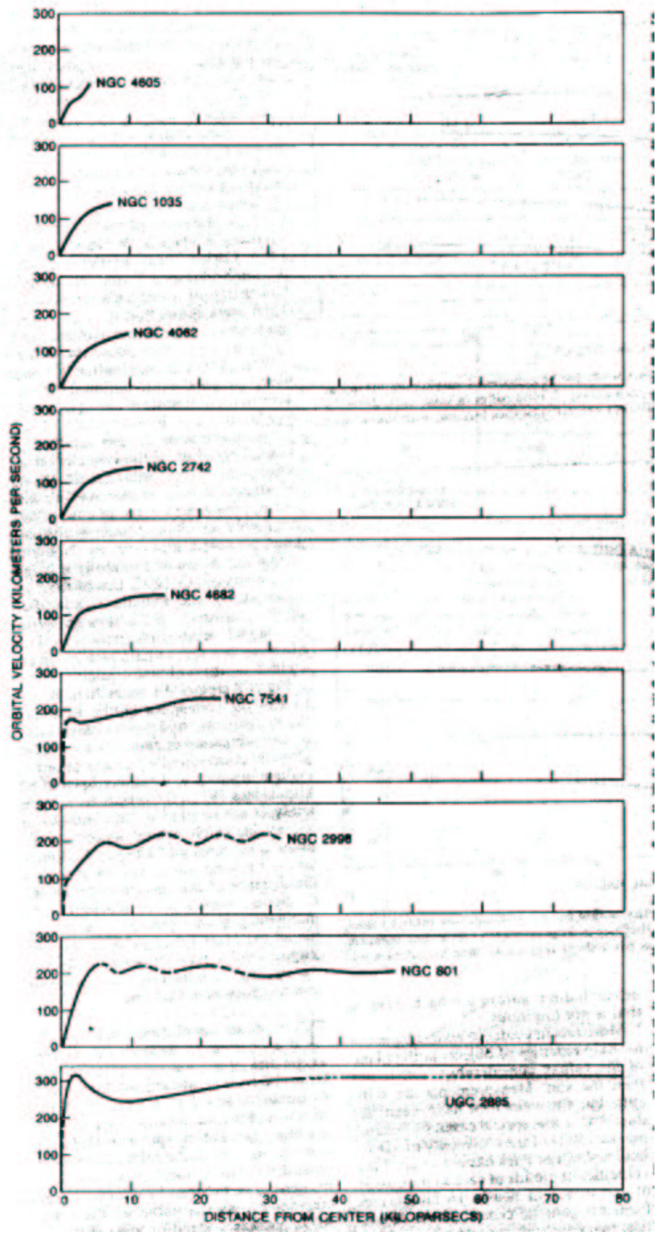

Figure 2: ROTATION CURVES of nine Sc galaxies

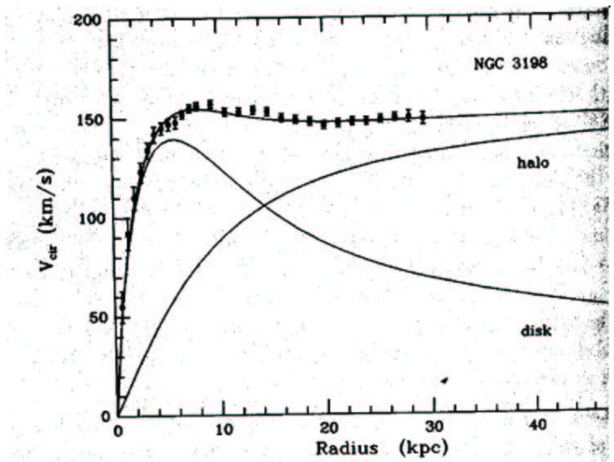

Figure 3: The Sc galaxy NGC 3198

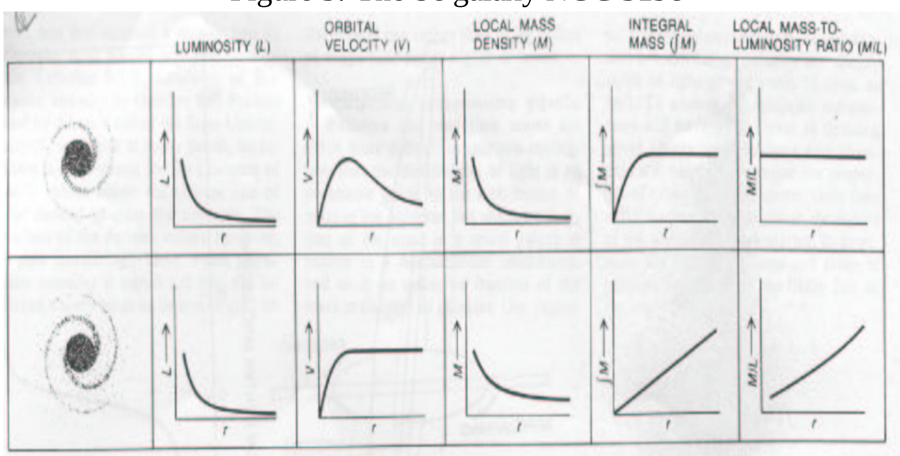

Figure 4: HYPOTHETICAL AND ACTUAL GALAXIES deviate sharply except in luminosity

Because all the quantities on R.H.S. are known from observation, Q can be found.

(b) Virial Theorem

Another possibility is to use the velocity dispersion of the stars in the ellipticals and determine the total mass by using virial theorem.There is a difficulty in this procedure - we need a handle on the velocity anisotropy in order to obtain a reliable estimate of the mass.

(c) X-ray halos

Many-and possibly all luminous elliptical galaxies contain up to $10^{10} M_\odot$ of hot, X-ray emitting gas.The gas is produced by normal stellar mass loss.The X-rays are continuum photons emitted by gas at temperature $\approx 10^7$ K as it cools through he bremsstrahlung process. Since the cooling rate per ion is proportional to the local electron density, cooling will dominate over heating at small radii, where the density is high.Thus the gas in the central regions will steadily cool and flow in to the center of the galaxy.The flow velocity is much less, so that approximate hydrostatic equilibrium is maintained in the gas.

In a spherically symmetric galaxy, hydrostatic equilibrium implies

$$\frac{dp}{dr} = -\frac{GM(r)\rho}{r^2}, \tag{13}$$

where ρ and p are the density and pressure, and $M(r)$ is the mass interior to radius r. Using the ideal gas law, this can be rewritten as

$$M(r) = \frac{k_B T r}{G \mu m_p}\left[-\frac{dln\rho}{dlnr} - \frac{dlnT}{dlnr}\right], \tag{14}$$

where T is the gas temperature, μ is the mean molecular weight, and m_p is the proton mass. Since the gas is optically thin, and the luminosity density at any radius is proportional to the square of the density in a fully ionized gas,we can determine the density profile $dln\rho/dlnr$ in Eq. (14), if the temperature is known. The mean temperature can be determined by fitting the X-ray spectrum to a bremsstrahlung spectrum. The spatially resolved temperature measurements give the temperature profile.

3 Dark Matter in Systems of Galaxies

3.1 Dark Matter in Groups of Galaxies

Groups of galaxies contain typically 10-100 galaxies with a mean separation that is much smaller than the typical intergalactic separation in the universe. The masses of these groups can be estimated if we assume that they are gravitationally bound systems in steady state. For such systems, virial theorem gives the relation $2T + U = 0$, where T is the kinetic energy and U is the potential energy of the system.For a group of N galaxies, treated as point masses with masses m_i, positions

$\mathbf{r_i}$, and velocities $\mathbf{v_i}$, the virial theorem can be written as

$$\sum_{i=1}^{N} m_i v_i^2 = \sum_{i \neq j}^{N} \frac{G m_i m_j}{|\mathbf{r_i} - \mathbf{r_j}|}. \tag{15}$$

Observationally, we can determine only the line-of-sight velocity dispersion σ^2 and the projection R_i of r_i onto the plane of the sky. On the average, we expect $v_i^2 = 3\sigma^2$; we can relate the projected inverse separation to the true inverse separation by averaging over all possible orientations of the group.It can be shown that:

$$< (|\mathbf{R_i} - \mathbf{R_j}|)^{-\mathbf{1}} >= \frac{\pi}{2}(|\mathbf{r_i} - \mathbf{r_j}|)^{-1}. \tag{16}$$

We also assume that the mass-to-light ratios Q of all the member galaxies are the same. Substituting $m_i = QL_i$ into the virial equation and using Eq.(16) we get

$$Q_{group} = \frac{3\pi}{2G} \frac{\sum_{i=1}^{N} L_i \sigma_i^2}{\sum_{i \neq j}^{N} L_i L_j (|\mathbf{R_i} - \mathbf{R_j}|^{-1})} \tag{17}$$

Because all the quantities on the R.H.S. can be determined from the observations, we can find Q for the group.

The median value of Q for several groups studied is $\sim 260hQ_{\odot}$. This procedure is applicable for groups with sufficiently large numbers of galaxies but this procedure needs to be modified if groups are dominated by a single large galaxy or if the dark-matter halo forms a uniform background around all the galaxies.

3.2 Dark Matter in Clusters of Galaxies

The Coma cluster of galaxies was the system in which Zwicky(1933) first found evidence for large amounts of dark matter, and rich clusters of galaxies provide some of the best available sites for studying the nature and distribution of dark matter.

(a) Modeling the Clusters

Clusters have the advantage of containing many more galaxies than typical groups.In some nearby clusters, several hundred galaxy velocities have been measured, thereby eliminating the statistical uncertainties that plague measurements of galaxy groups.The number of galaxies is so large that we can use the solutions of the collisionless Boltzmann equation to model the cluster. Such a procedure for the Coma cluster suggests mass-to-light ratio of $\sim 400hQ_{\odot}$.A similar analysis of the Perseus cluster gives a value of $600hQ_{\odot}$.Clearly, these clusters contain a large amount of dark matter.

(b) X-ray measurements

Like the individual galaxies discussed in section (2.4 (c)), many clusters of galaxies contain hot gas that emits X-rays. Since the gas is in hydrostatic equilibrium, it can be used to trace the gravitational potential and mass distribution in clusters using Eq. (14). the principal obstacle in applying this method is the absence of spatially resolved spectral information, so that the temperature gradient term $dlnT/dlnr$ in Eq. (14) must be estimated by indirect methods.

(c) Gravitational Lensing

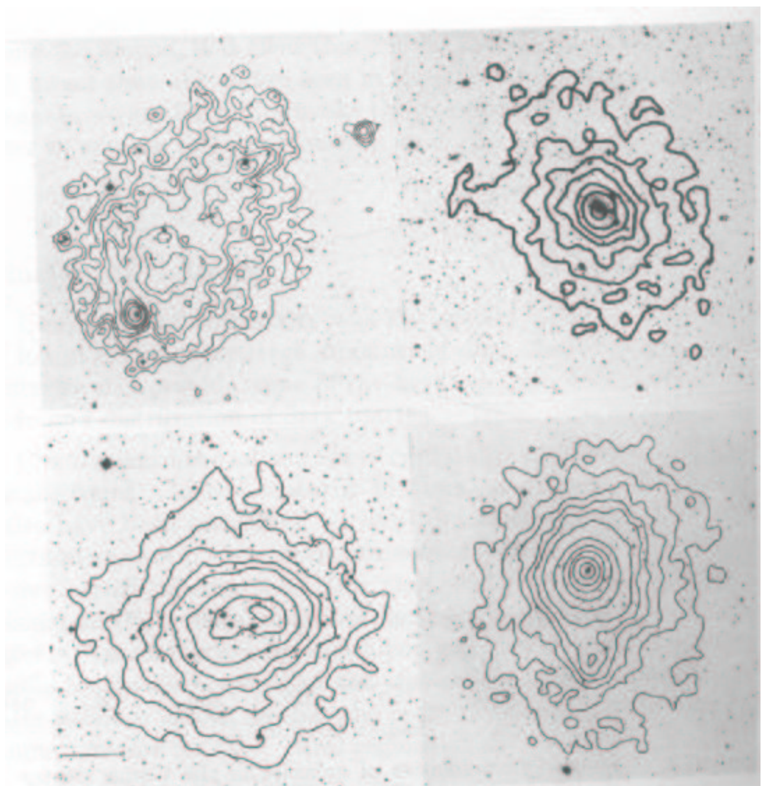

Figure 5: X-Ray contours on photographs of clusters of galaxies

The red shift measurements have provided strong dynamical evidence for dark matter on scales from galaxies to superclusters of galaxies but gravitational lensing of light is technique that does not rest on assumptions about stellar and galactic orbits.The simplest method of measuring cluster masses is from gravitational deflection of light.Galaxy clusters have masses of about $10^{1}4$ solar masses and are the most massive collapsed objects in the universe. Several clusters have been found to produce observable distortions on the images of background galaxies. There are two different regimes: i) The strong gravitational lensing: In some cases dramatic, luminous arcs are seen. ii) The weak gravitational lensing: More commonly, smaller distortions lead to arclet images and for nearly every cluster at the right distance, statistical use can be made of the distortions of background galaxy images to learn about the mass distribution of the cluster. This regime of weak lensing began to flourish after Kaiser and Squires (1993) developed a parameter-free method for reconstructing the surface mass density of galaxy clusters from their tidal shear effect on background galaxies.

The statistical distortion method starts from regions where the distortions are tiny, i.e. the outermost regions of galaxy clusters, and goes inward. It requires analyzing ellipticities and orientations of samples of faint distant background galaxies and averaging statistically the properties of their shapes over patches of sky to trace the cluster mass distribution or even to map mass distributions on larger scales from its shear field.

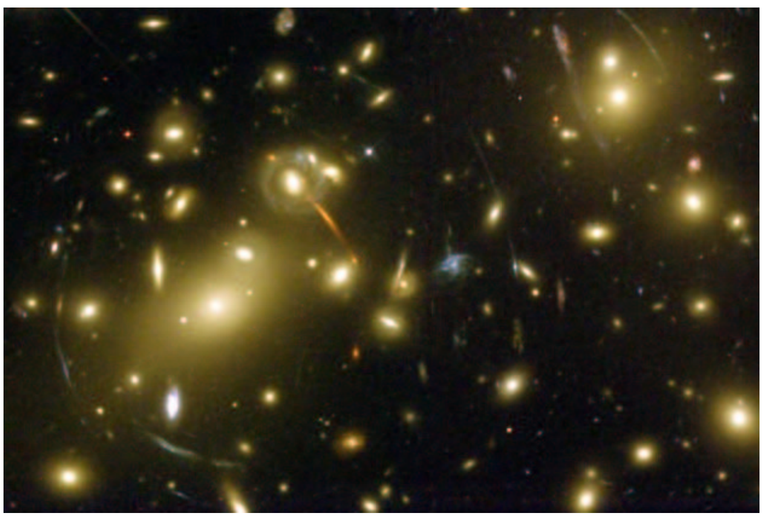

Figure 6: Gravitational lensing due to Abell Cluster

System	Method	Scale	$Q/Q_\odot$	Ω
Milky Way	Near sun	100 pc	5(?)	$0.003h^{-1}$(?)
	Escape velocity	20 kpc	30	$0.018h^{-1}$
	Satellites	100 kpc	30	$0.018h^{-1}$
	Magellanic stream	100 kpc	>80	$>0.05h^{-1}$
Ellipticals	Core fitting	2 kpc	$12h$	0.007
	X-ray halo	100 kpc	>750	$>0.46h^{-1}$
Spirals	Rotation curves	50 kpc	$>30h$	>0.018
Groups	Local group	800 kpc	100	$0.06h^{-1}$
	Other groups	1 Mpc	$260h$	0.16
Clusters	Coma	2 Mpc	$400h$	0.25

4 The Nature of the Dark Matter

It is clear that the density parameter Ω is at least ~ 0.2 over scales at which reasonably accurate dynamical measurements are possible. There is evidence that Ω increases with the scale. The luminous matter contributes only $\Omega = .01$.

Therefore, now i address the important question that what dark matter is composed of.*There is no a priori reason for the dark matter in different objects to be made of the same constituent.*For example, our analysis of dark matter near the Sun suggests that roughly half the mass in the solar neighborhood is not visible. this component of dark matter is *confined* to the galactic disk and hence must have undergone dissipation. It is therefore reasonable to conclude that this component must be baryonic.In fact, there *must* be baryonic dark matter even at larger scale.This is because the dark matter in the solar neighborhood contributes only $\Omega \approx 0.003$, which is at least a factor of 4 less than the *lower* limit on the baryonic density arising from the nucleosynthesis bounds. Rich clusters contain a significant fraction of baryons.The luminous baryon component amounts to only $\Omega \approx 0.003$ in stars.Hence it is obvious that we are missing quite a fraction of baryons seen at $z \approx 3$ by the time we reach $z \approx 0.0$

But it is unlikely that *all* the dark matter in the universe is contributed by baryons.There are two reasons for this conclusion: (1) The baryonic universes with $\Omega_B \approx 0.2$ violate the MBR anisotropy observations.(2)$\Omega = 0.3$ observation can not be contributed entirely by baryons, because such a case would violate the upper bounds on Ω_B arising from the nucleosynthesis.

The preceding arguments, taken together, suggest that *both* baryonic and nonbaryonic dark matter exist in the universe, with nonbaryonic matter being dominant. Now I take up the two components separately.

4.1 Baryonic Dark Matter

Baryonic dark matter can exist in several forms.

Low luminosity stars and stellar remnants

One possible explanation is that the star formation process happens to convert most of a given mass of interstellar gas into **brown dwarfs**, that is, stars with masses too low to burn hydrogen(¡ 0.08 $M_\odot$).However, the standard theory of star formation predicts very few stars with masses of less than $0.08 M_\odot$. Therefore, in order for this model to be feasible, the IMF governing the star formation must have a nonstandard shape. Because the process of star formation is not quite well understood, such a possibility cannot be ruled out at this stage.

The baryonic dark matter could also be in the form of white dwarfs, neutron stars, or black holes, all of which are remnants of stellar evolution. There is a constraint on the density that can be contributed by such remnants that arises from the fact that stellar evolution should not contribute too much to the background radiation. This constraint gives $\Omega < 0.03$.We require a contrived IMF between 2 and 8 $M_\odot$ to avoid excessive production of light or metals.Further, a large fraction of white dwarf precursors in binaries will also lead to an excessive number of type IA supernovae.More recent constraints come from CNO,He, and D production, as well as limits on the EBL; these have strengthened the belief that white dwarfs are unlikely candidates.

Primordial black holes

Another possibility is for the baryons to exist in the form of primordial black holes. This can happen in scenarios in which there existed an epoch of star formation *before* the onset of galaxy formation.In such a case, the primordial stars, heavier than a few hundred solar masses, can collapse directly, forming a black hole. This is to be contrasted with the black holes produced in standard stellar evolution, in which much of the stellar mass is expelled during the black hole formation. The latter case is severely constrained by the fact that the concentration of heavy elements in the ISM should not be too large(the resulting bound is $\Omega < 10^{-4}$). The bounds are much less severe on the formation of black holes directly from supermassive stars with masses in the range $10^2 M_\odot < M < 10^6 M_\odot$.(the upper bound of $10^6 M_\odot$ comes from the fact that gravitational perturbation from the black holes should not heat up the disk stars too much.)There are, however, several other indirect constraints on the existence of such supermassive black holes.

Massive Astrophysical Compact Halo Objects

This relates to an important application of the lensing by point mass - a phenomenon called *microlensing*.If, e.g. a compact object in our galaxy moves across a distant star in, say, a LMC, it will lead to a magnification of the light from star under optimal conditions. The probability for lensing is low and hence it is necessary to monitor a large number of stars for a long period of time in order to produce significant effects. It is necessary to distinguish the variation in the light curve of the star caused by microlensing from the intrinsic variability of the star.By and large, this is feasible because microlensing produces light curves that are symmetric with respect to the peak - unlike those produced by intrinsic variability.

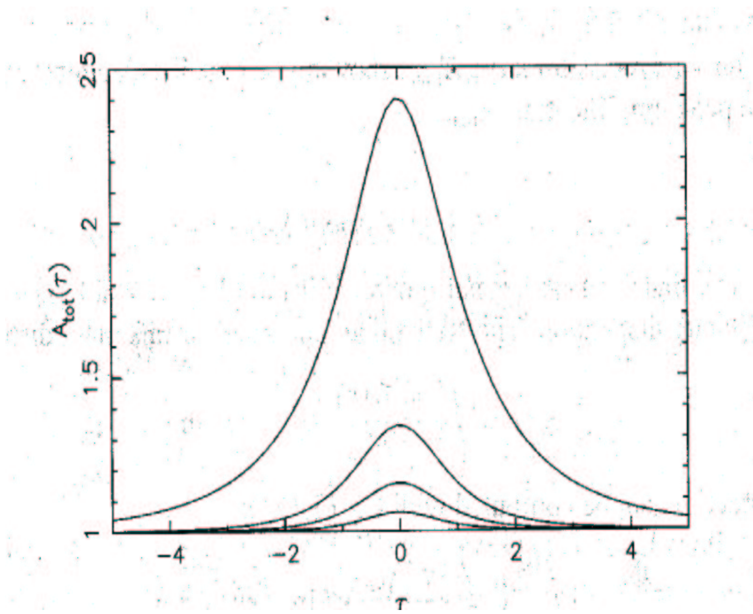

Figure 7: Microlensing

In 1989 two experiments started with the purpose of monitoring millions of stars for microlensing to detect dark matter. The EROS collaboration, consisting mostly of French astrophysicists and particle physicists, used a telescope in South America, while the MACHO collaboration of American and Australian scientists used a telescope in Australia. In 1993, the first such event was announced by MACHO collaboration.It seems from these experiments that while a portion of the dark matter may consist of MACHOs, the bulk of it cannot. Thus, the need to search for non-baryonic dark matter becomes more important than ever. With the microlensing results, it becomes clear that even the dark matter in the halo of the Milky Way must consist mostly of some quite exotic material, such as a new type of elementary particle.

Other forms of baryonic matter

There are constraints on many other forms of baryonic dark matter. For example, small objects like dust grains, asteroids, comets, etc.(which are dominated by molecular forces rather than by gravitational forces) cannot contribute much to dark matter. This is because such bodies will be composed of heavy elements like Si, C, etc., which are always much less abundant than H. par Elliptical galaxies and clusters do contain a hot gas. made of baryons, which is detectable from x-ray emission. however the mass in the gaseous component is not dynamically significant.Similarly, observations from the 21-cm line of neutral-H clouds show that the neutral gas present around galaxies is also not dynamically significant.

4.2 Non-baryonic Dark Matter

The balance of cosmological evidence, especially primordial nucleosynthesis favors that dark matter consists of weakly interacting relic particles.

In conventional cosmology, the matter content of the universe at nucleosynthesis consisted of baryons, photons and three species of neutrinos. There are therefore two distinct ways forward: either the neutrinos have mass, or there must exist some additional species that is frozen-out relic from an early stage of the big bang. A small mass for neutrinos would not affect nucleosynthesis, as the neutrinos would be ultrarelativistic at this time (prior to matter-radiation equality). Other relic particles have to be either very rare or extremely weakly coupled (i.e. more weakly than neutrinos) in order not to affect nucleosynthesis. Either alternative would yield a form of dark matter that is collisionless.

Other than massive neutrino there are other candidates for a relic particle that could close the universe.There are other alternatives which lie outside the standard model: the axion and various supersymmetric particles.A common collective term for all these particles is **WIMP** , standing for weakly interacting massive particle.

There are three generic types to consider

HOT DARK MATTER
These are particles that decouple when relativistic, and which have a number density roughly equal to that of photons; eV-mass neutrinos are the archetype here. Consider the average energy for massless thermal quanta:

$$< E >= \begin{cases} 2.701kT & \text{(bosons)} \\ 3.151kT & \text{(fermions)}. \end{cases} \tag{18}$$

For a massless particle, $< E >$ is related to the mean momentum via $< E >=< |p| > c$. As the universe expands and the particles cool and go non relativistic, the momentum is red shifted, eventually becoming just $m|v|$. At late times, the neutrino momentum distribution still has the zero-mass form, so we should use the above relations with $E \rightarrow m|v|c$. This gives a velocity

$$< |v| >= 158(m/eV)^{-1}kms^{-1} \tag{19}$$

for neutrinos with $T = 1.95K$, so low mass relics are hot in the sense of possessing large quasi-thermal velocities.These velocities were larger at high redshifts, leading to major effects on the development of self-gravitating structures.

WARM DARK MATTER (WDM)
To reduce the present-day velocity while retaining particles that decouple when relativistic, the present density(and hence temperature) relative to photons must be reduced. this is possible if the particle decouples sufficiently early, since the relative abundance of photons can then be boosted by annihilations other than just $e^{\pm}$. In grand unified theories there are of order 100 distinct particle species, so the critical mass can be boosted to around 1-10 keV.

COLD DARK MATTER (CDM)
If the relic particles decouple while they are non relativistic, the number density can be exponentially suppressed and so the mass can apparently be as large as is desired - and the thermal velocities effectively zero, justifying the name 'cold'. If the decoupling occurs at very high redshift, the horizon scale at that time is very small and so negligible damping occurs through free streaming. Structure formation in a CDM universe is then a **hierarchical** process in which nonlinear structures grow via the merger of very small initial units.The only category that can produce models that are consistent with data on the spatial distribution of galaxies is cold dark matter.If we assume that the CDM particle interacts via the weak interaction, then the abundance as a function of mass can be calculated

The essential features of this calculation are that for small masses we have just the standard massive-neutrino result: the relic density is the product of the conventional number density for massless neutrinos and the particle mass, so $\Omega\alpha m$. a critical density thus requires a neutrino mass of order 100 eV, and much higher masses are ruled out:

$$\Omega_\nu h^2 = \frac{\sum m_i}{93.5eV}, \tag{20}$$

where the sum is over different neutrino species. This continues until masses of a few MeV ($\Omega \sim 10^4$), at which point the neutrinos cease to be relativistic at decoupling. In this mass regime, the relic co-moving number density of neutrinos is reduced by annihilation.In the non relativistic limit, the number density of thermal particles is,

$$n = g(\frac{mT}{2\pi})^{3/2} e^{-m/T}. \tag{21}$$

It appears that the relic abundance should fall exponentially with mass m, but it can be shown that relic density falls as m^{-2}.

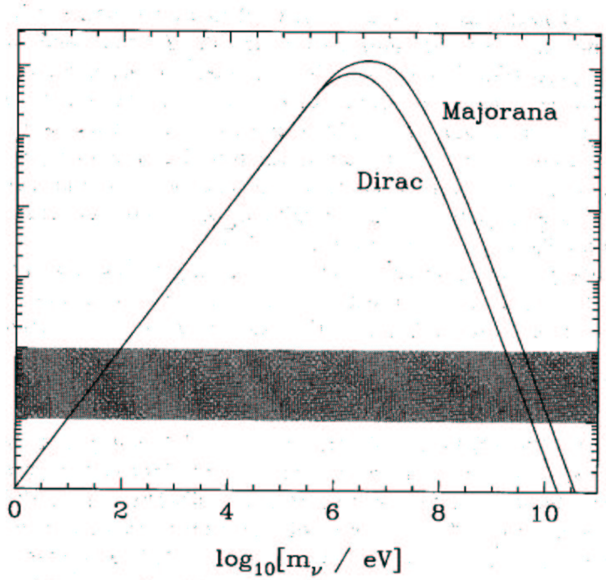

Figure 8: Density parameter vs rest mass of relic neutrinos

The exact curve depends on whether the neutrinos are Majorana or Dirac.The universe can also be closed by massive neutrino-like particles with masses around

3 GeV. Lower masses are disallowed (the **Lee-Weinberg limit**), until we reach the light-neutrino point around 30 eV.

The ways in which CDM can be realised in practice are twofold.The particle may have weaker interactions than a neutrino, which is possible with some of the super-symmetric candidates (in which case GeV-scale masses are possible), and with axion (although the mass is very small in this case).It is also possible that the $\Omega(m)$ curve may reverse once more at higher energies, since cross-sections alter beyond the electroweak scale at $\sim 100 GeV$. This could conceivably allow neutrino-like WIMPs with masses $\sim 1 TeV$.

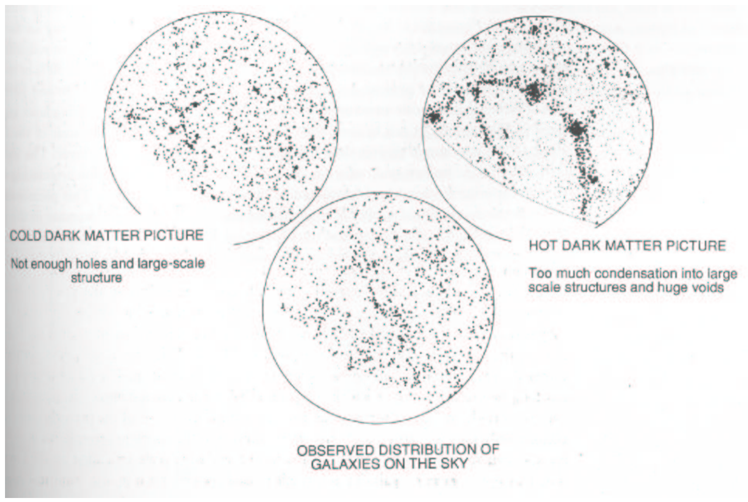

Figure 9: Simulations by Carlos Frenk

5 New Physics

All of the discussion so far has been based on the premise that Newtonian gravity and general relativity are correct on large scales.In 1989, Mordehai Milgrom proposed a modification of Newton's second law of motion. This law states F=ma. This law has never been verified when a is extremely small. And that is exactly what's happening at the scale of galaxies, where the distances between stars are so large that the gravitational force is extremely small.The acceleration set of equations for the Modified Newtonian Dynamics:

$$F = m\mu(a/a_0)a \tag{22}$$

$$\mu(x) = \begin{cases} x & \text{if } x < 1 \\ 1 & \text{if } x > 1 \end{cases} \tag{23}$$

The exact form of μ is unspecified, only its behavior when the argument x is small or large. As Milgrom proved in his original paper, the form of μ doesn't change the consequences of the theory but...

New evidence from NASA's Chandra X-ray Observatory challenges an alternative theory of gravity that eliminates the need for dark matter. An observation of the galaxy NGC 720 shows it is enveloped in a slightly flattened, or ellipsoidal cloud of hot gas that has an orientation different from that of the optical image of the galaxy. The flattening is too large to be explained by theories in which stars and gas are assumed to contain most of the mass in the galaxy. ”The shape and orientation of the hot gas cloud require it to be confined by an egg-shaped dark matter halo,” said a researcher involved in the study. ”This means that dark matter is not just an illusion due to a shortcoming of the standard theory of gravity–it is real.”

6 Summary

There is strong evidence that on all scales larger than that of the open clusters and globular clusters there is a strong evidence that a substantial fraction of the total mass in some form which we cannot detect except by its gravitational effects.There is dark matter in the solar neighborhood, int he outer parts of individual galaxies, in groups and clusters of galaxies, and in the Virgo supercluster.The ratio of dark to luminous matter increases in systems of larger size, but the mean density of dark matter implied by dynamical measurements does not appear to be sufficient to close the Universe. Both baryonic and non-baryonic dark matter exist and non-baryonic is dominant one.

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