Dark Matter in the Universe

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We treat here the problem of dark matter in galaxies. Recent articles seem to imply that we are entering into the precision era of cosmology, implying that all of the basic physics of cosmology is known. However, we show here that recent observations question the pillar of the standard model: the presence of nonbaryonic "dark matter" in galaxies. Using Newton's law of gravitation, observations indicate that most of the matter in galaxies is invisible or dark. From the observed abundances of light elements, dark matter in galaxies must be primarily nonbaryonic. The standard model and its problems in explaining nonbaryonic dark matter will first be discussed. This will be followed by a discussion of a modification of Newton's law of gravitation to explain dark matter in galaxies.

I Introduction

The matter producing the visible light in galaxies is only $\sim 0.1\%$ of the amount of matter necessary to produce the approximate flat universe, which present observations indicate. While part of the dark matter in galaxies is baryonic, the major part is assumed to be nonbaryonic in the standard model. Present observations indicate that this analysis of the dark matter in galaxies may not be true. In section II we discuss dark matter in galaxies as understood in the standard model, as well as the difficulties with such an interpretation. A modification of Newton's law of gravitation in order to explain the dark matter in galaxies is treated in Section III. Finally, in section IV, we present our conclusions.

II The standard model of dark matter in galaxies and its problems

A. The standard model

According to the standard model, early in the universe, there ocurred an epoch of expansion that was exponential in time. This exponential expansion is generally attributed to be due to a scalar (*inflaton*) field. Quantum fluctuations of the scalar field eventually created fluctuations in the density (i.e., adiabatic fluctuations). Due to the expansion of the universe, the relativistic particles, such as photons and neutrinos, cooled faster then the non-relativistic particles, such as baryons and WIMPS (weakly interacting massive particles, which are called cold dark matter (CDM)). When non-relativistic particles began to dominate the universe (i.e., the matter-dominated epoch), the fluctuations of CDM began to grow. At the recombination epoch, when hydrogen atoms formed and the cosmic microwave background (CMB) was created, baryons (i.e., hydrogen, helium, etc.) began to fall into the gravitational potential wells created by the growing CDM fluctuations. The smallest mass fluctuations that collapsed had masses $\sim 10^6 M_\odot$. They eventually coalesced to form the observed galaxies ($\sim 10^{12} M_\odot$) and clusters of galaxies ($\sim 10^{15} M_\odot$). This model for the formation of galaxies and clusters of galaxies involves, however, a number of problems, which we discuss in the following sub-sections.

B. Smooth rotation curves of galaxies

The dark matter content of spiral galaxies is primarily determined from their rotation curves. We can determine the velocities of hydrogen atoms in distant parts from the center of a spiral galaxy by their Doppler-shifted 21 cm lines, observed by radio telescopes. From Newton's law of gravitation, the amount of matter within a radius R from the center determines the circular velocity of a hydrogen atom. We find from observations that the circular velocity, V_c, rises initially with radius, as expected, but then becomes approximately constant with radius, which is unexpected. If matter were indeed confined to within a radius R_m, we should expect $V_c^2 R =$ Constant for $R > R_m$, from Newton's law.

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In the standard model, a spiral galaxy consists of CDM and baryonic matter. The baryonic matter, subject to electromagnetic dissipation processes, collapsed and formed the disk of the galaxy. We therefore expect to have all of the baryonic matter (primarally confined to a disk) in the inner part of the galaxy, and the outer part of the galaxy (the halo) to be dominated by CDM (weakly interacting matter) which is not subject to electromagnetic dissipation processes. From Newton's law, we have $V_c^2 R = GM_{\rm R}$, where $M_{\rm R}$ is the mass within the radius R and G is the gravitational constant. We expect a "break", or discontinuity, in the curve V_c vs R when R passes from the disk to the halo since the baryonic density of the disk has little to do with the CDM density of the halo. However the expected break does not exist. This was first noticed by Bahcall and Casertano [1], who called it the "disk-halo conspiracy". Casertano and van Gorken [2] noted that whatever feature does exist, it is less than 10%. Blumenthal et al. [3] noted that if CDM dominated at all radii, then a featureless V_c vs R curve should be seen. Observations, however, indicate that for small radii, at least in our galaxy near the sun, CDM does in fact, not dominate the matter content. These obsevations appear to imply that CDM interacts strongly with the baryonic matter (e.g., electromagnetically), whereas according to the standard model, they should only interact weakly (i.e., gravitationally).

C. Surface brightness of galaxies

Galaxies have the same asymptotic circular velocity, V_{c_∞} (for a given luminosity) whether they have a high or low surface brightness. This peculiar fact was noted by Zwan et al. [4], Sprayberry et al. [5] and Mc Gaugh et al. [6]. In the standard model, we require that the mass to light ratio increases (i.e., more CDM) in order to compensate for the low surface brightness and preserve the same Luminosity vs V_{c_∞} dependency. It is, thus, implied that the CDM somehow knows what the baryonic matter is doing, which is not the case in the standard model since there is negligible interaction between CDM and baryonic matter.

D. Evidence for CDM

It is generally observed that evidence for CDM only exists in regions with gravitational accelerations $< 10^{-8}$ cm s^{-2} [7], [8]. There is, however, no characteristic acceleration $a_0 \sim 10^{-8}$ cm s^{-2} in the standard model.

E. Parameters to describe rotation curves

The standard model requires two parameters to describe the curves V_c^2/R vs R. The two parameters frequently used are V_{c_∞}, the asymptotic circular velocity, and R_e, the effective radius of the spiral galaxy, where the surface brightness drops to 1/2 its central value. However, the curves, can be shown to be very well described by the relation $V_c^2/R = a_{\rm N}(1+x^2)^{1/2}/x$, where $a_{\rm N} = GM_{\rm R}/R^2$, $x = a_{\rm N}/a_0$, and $a_0 = 10^{-8}$ cm sec^{-2}. a_0 is the only parameter required. In the standard model, with the baryonic matter and CDM fairly independent, it is reasonable that we should require two parameters to describe rotation curves: one for baryonic matter content and the second for CDM. Since only one parameter, is in fact required (a_0), the matter content of the spiral galaxy does not appear to have two independent components.

F. Galactic discs

The standard model predicts galactic discs which are too small compared to observations. In the standard model, the angular momentum of the discs created by numerical simulations, is about 10% of what is observed [9]. A feedback scenario, in which star-formation helps prevent baryonic matter to lose angular momentum to the CDM halo, does not resolve the problem [10].

G. Centers of galaxies

According to the standard model, CDM interacts only weakly (i.e., gravitationally). From Liouville's theorem and the fact that in the past, the distribution of CDM was approximately homogeneous, all the centers of CDM objects (i.e., the centers of galaxies) should have the same maximum phase space. This, however, is not observed [11].

H. Cusps in the centers of galaxies

Simulations with CDM predict singular central densities ("cusps") in galaxies, which, however, are not observed [12], [13]. Describing the central density by an *index of concentration*, the index is found to vary greatly from galaxy to galaxy [14]. In general, rotation curves indicate central galactic densities (including the Milky Way) which are much less than predicted by the standard model [15].

I. L vs V_{c_∞}

Numerical calculations with CDM predict a Luminosity vs V_{c_∞} which is not in agreement with observations. The predicted L vs V_{c_∞} curves with CDM predict too high a V_{c_∞}, as compared with observations [15].

J. Dwarf galaxies

The number of dwarf galaxies is predicted by the standard model to be 10 times more than is observed. This has been noted by Klypin et al. [16] and Moore et al. [13].

K. L vs $V^4_{c_\infty}$

Numerical calculations with CDM indicate L vs $V^3_{c_\infty}$, however, what is observed is L vs $V^4_{c_\infty}$, as noted by Dalcanton et al. [17] and Mo et al., [18].

L. Surface density of galaxies

Observations indicate a cut-off of high surface density discs in spiral galaxies (*Freeman Law*) as well as a cut-off of high density elliptical galaxies (*Fish Law*). The cut-off occurs for a surface density $\Sigma_c \simeq 10^{-8}$ cm s^{-2}. The standard model does not predict these cut-offs.

M. Acoustic peaks of cosmic microwave background (CMB)

The standard model with CDM predicts a second acoustic peak much higher than observed. There is, however, no obvious explanation for this in the standard model.

N. Self-interacting CDM

In order to help with the large number of dwarf galaxies that the standard model predicts, a modification of the standard CDM scenario has been made by assuming that the WIMPS have a large scattering but a small annhilation cross section among themselves [19]-[21]. Although this modification helps with the number of dwarf galaxies [22]-[24], the other problems cited above, such as forming cusps, remain [25].

III Modification of Newton's law of gravitation in order to explain the dark matter in galaxies

We discuss here the evidence indicating that a simple modification of Newton's law of gravitation for small accelerations, $g < a_0 = 10^{-8}$ cm s^{-2}, is in better agreement with observations than the standard model employing CDM. Such a model was suggested by Milgrom [26] who named it MOND (Modified Newtonion Dynamics).

If g_N is the acceleration predicted by Newton's law, MOND suggests that the true acceleration is given by $g = g_N/\mu(x)$, where $\mu(x)$ is a monotonic function of x and $x = g/a_0$. The function $\mu(x)$ has the properties $\mu(x) \simeq 1$ for $x >> 1$ and $\mu(x) \simeq x << 1$. In particular, Milgrom [26] suggested the function $\mu(x) = x/(1+x^2)^{1/2}$, which is generally used in the literature and which we use in the rest of this section.

A. The rotation curves in our galaxy

Lépine and Leroy [27] studied the rotation curve (circular velocity V_c) data (V_c vs R) in our galaxy. From the mass distribution of the disk and the bulge, the sum was found to give a V_c vs R curve in very good agreement with the observed data. In particular, they found that "... there is no need for a dark matter component". The data was analyzed for $R < 10$ k pc. Thus the gravitational accelerations responsible for the rotation curve are $> 3.2 \times 10^{-8}$ cms^{-2}. These results are in agreement with MOND, where $x > 1$ and $g \simeq g_N$, which predicts no CDM.

B. Spiral galaxies

Sanders and Verheijen [28] studied the rotation curves of 30 galaxies in a nearby cluster of galaxies, at a distance of $\sim 15Mpc$. They found very good agrrement with the MOND prediction.

C. Low surface brightness galaxies

A low surface brightness galaxy has a surface brightness $\sim 1/2$ that of a normal galaxy. However, its atomic hydrogen content is normal. The galaxies are not dwarf galaxies, but have masses on the order of normal galaxies. de Blok & Mc Gaugh [29] studied the rotation curves of 15 such galaxies and found that they were in agreement with MOND.

D. Stability of galactic discs

Normally a massive CDM halo is invoked as the source of stability of a Newtonian disc. However, MOND predicts greater stability of galactic discs than does Newtonian theory and, thus, does not have to rely on CDM. Brada and Milgrom [30] found that the extra stability in the MOND theory was equivalent to the presence of a massive halo with a mass three times that of the disc.

E. Galactic warps

The discs of spiral galaxies are not completely flat, but are warped at their edges. The origin of the warps of these galaxies can not be understood using Newtonian dynamics. The tidal force of the Magellanic cloud acting on our galaxy is not enough to create the obseved warp. Brada and Milgrom [31] showed that using MOND, the Magellanic cloud creates the observed warp in our disc.

F. Dwarf galaxies

Our galaxy has many nearby dwarf galaxies. Using MOND, Brada and Milgrom [32] made the prediction that the size of a dwarf galaxy should be inversely proportional to the distance to our galaxy and its surface density, proportional to this distance. Müller and Opher [33] made the prediction, that stellar orbits in dwarf galaxies are more stable if they are perpendicular to the line-of-sight to the Milky Way. These predictions should be able to be verified (or shown to be incorrect) in the near future.

G. Groups of galaxies

Milgrom [34] applied MOND to the study of groups of galaxies in the Las Campanas Redshift Survey (LCRS) [35], the CfA1 survey [36], and the CfA2 survey [37]. The number of groups studied were 394 in LCRS, 166 in CfA1, and 406 in CfA2. Using the standard model for these groups, the average mass to light ratios found (in solar mass to light units) were 115 for LCRS, 198 for CfA1, and 180, for CfA2. Using MOND, the mass to light ratios found were ~ 3.7 for LCRS, ~ 2.4 for CfA1, and ~ 8.6 for CfA2. Whereas considerable CDM is indicated for the groups using the standard model, little or no CDM is indicated using MOND.

H. (CDM) vs (NO CDM) in the CMB

One of the most important sources of information on the early universe is the cosmic microwave background (CMB). The intensity of the CMB is measured in degrees Kelvin of an effective black body that could produce the CMB. The fluctuations of the temperature ΔT over the sky can be expanded in Legendre polynomials (i.e., the CMB may be studied by determining amplitudes of the Legendre polynomials as a function of l, the order of the Legendre polynomial). A plot of ΔT vs l, which depends on the input physics, can be obtained from a public domain code, CMBFAST [38]. The standard model predicts acoustic peaks at $l \sim 220$ and $l \sim 440$. The values for these first and second acoustic peaks are $\Delta T \sim 65\mu K$ and $\Delta T \sim 50\mu K$, respectively. What is observed, however, is a much smaller second acoustic peak. Mc Gaugh [39], [40] showed that if there were no CDM, and only baryonic matter, theory would then be in agreement with observations.

I. Creating inhomogeneities with MOND

Sanders [41] investigated the creation of inhomogeneities according to MOND. The simplified theory that was used was: if the Newtonian gravitational acceleration $g_{\rm N}$ is greater than $a_0(\simeq 1.2 \times 10^{-8}\ {\rm cm\,s^{-2}})$, it is unaltered, whereas if the Newtonian acceleration is less than a_0, it is increased to the value $\sqrt{(}g_{\rm N}a_0)$. This value for the acceleration is obtained taking the extreme MOND limit, when $\mu(x) \to x$ for $x < 1$ and $\mu(x) = 1$ for $x > 1$.

The surfaces of small spheres have small gravitational deaccelerations with respect to the centers of the spheres. These spheres are thus in the MOND limit. The maximum (critical) radius of a sphere that is in the MOND limit is $R_c = a_0/G\rho_{\rm M}(4\pi/3)$, where $\rho_{\rm M}$ is the matter density of the sphere. The critical mass of this sphere is $M_c = (4\pi/3)R_c^3\rho_{\rm M}$.

In the standard model, the epoch of equipartition (when the matter density is equal to the radiation density) occurs at a redshift $z \sim 10,000$. If there is no CDM, however, and only baryonic matter, the epoch of equipartition occurs at a redshift $z \sim 222$. The critical mass at this epoch is $M_c = 3.7 \times 10^9 M_\odot$.

After the epoch of equipartition, the radiation pressure is negligible. At high redshifts, the effect of a cosmological constant is also negligible. If R_i ($< R_{c_i}$) is the radius of a sphere at the equipartition epoch, the deacceleration of the surface is proportional to R^{-1}. When $R_i > R_c$, then the deacceleration is proportional to R^{-2}. The velocity of the surface has a logarthmic dependence on R for $R_i < R_c$, whereas it has a R^{-1} dependence for $R_i > R_c$.

Starting at the equipartition epoch, a sphere initially expands with the Hubble flow, reaches a maximum radius, and then collapses. The equipartition epoch redshift, $z = 222$, occurs at a time $\sim 10^7$ years after the Big Bang. A sphere of $10^5 M_\odot$ reaches its maximum radius at a redshift $z \sim 150$, whereas a sphere of galactic mass $\sim 10^{11} M_\odot$ reaches its maximum radius at $z \sim 25$. Present observations indicate that galaxies formed at a redshift $z \sim 25$, in agreement with this model which does not include CDM.

IV Conclusions

The afirmation that we are entering into "the precision era of cosmology" appears in various recent articles. This phrase implies that we understand all of the basic physics and that all we need to do now is to measure the important parameters to several decimal places. This is reminiscent of the way that physicists talked when entering the $20^{\rm th}$ century a hundred years ago, before quantum mechanics and relativity were discovered. I hope to have shown in sections II and III that present observations question the existence of one of the pillars of the standard model, the presence of CDM in galaxies. A model such as MOND, which assumes that CDM does not exist, seems to fit the observations of galaxies better than does the standard model.

I have not tried to argue here that CDM definitely does not exist nor that MOND is definitely the true law of gravitation. I only wish to show here that we are def initely not in "the precision era of cosmology" and, on the contrary, are still struggling to understand the formation of galaxies.

It is on the scale of galaxies that a large amount of observational data is available and where the problems with the standard model have, consequently, been discovered. On a large scale, the observational data are not detailed and problems with the standard model are not evident.

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