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# Baryonic Matter Abundance in the Framework of MONG †

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**Abstract:** It is well established from various pieces of observational evidence that the relative abundance of baryonic matter in the Universe is less than 5%. The remaining 95% is made up of dark matter (DM) and dark energy. In view of the negative results from dark matter detection experiments running for several years, we had earlier proposed alternate models (which do not require DM) by postulating a minimal field strength (analogous to minimal curvature) and a minimal acceleration. These postulates led to the Modification of Newtonian Dynamics (MOND) and Modification of Newtonian Gravity (MONG), respectively. Some of the independent results that support the existence of non-baryonic matter are the mass–radius relation (that holds true for any gravitationally bound large-scale structure), Eddington luminosity, etc. Here, we discuss how these physical implications can be accounted for from the results of MONG without invoking DM.

**Keywords:** dark matter; modification of Newtonian dynamics; modification of Newtonian gravity; matter abundance

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## 1. Introduction

Measurements from cosmic microwave background radiation and elemental abundances from big bang nucleosynthesis imply that the universe is composed of 68.3% dark energy, 26.8% dark matter, and 4.9% ordinary baryonic matter [1]. Various cosmological observations, such as the dynamics of large-scale structures (galaxies and galaxy clusters), gravitational lensing, and X-ray observations implying the presence of hot gas in clusters, confirm the presence of non-baryonic invisible matter (DM). The presence of dark matter, though well established by indirect evidence, still remains undetected in various DM detection experiments that have been running for several decades [2]. The negative results of these experiments lead to a possible need to consider alternate models of dark matter that could explain the cosmological phenomena usually attributed to DM [3].

The modification of Newtonian Dynamics (MOND) is one such alternate model that was proposed by Milgrom [4] as an alternative to dark matter that accounts for the observed flat rotation curves of galaxies. However, this theory involves an ad hoc introduction of a fundamental acceleration, $a_0 \approx 10^{-8}\ \mathrm{cms}^{-2}$ [5]. As the acceleration approaches $a_0$, the Newtonian law is modified, and the field strength takes the form of

$$a = \frac{(GMa_0)^{1/2}}{r} \tag{1}$$

where $a$ is acceleration, $r$ is radial distance, and $M$ is the central mass. Equation (1) provides a constant velocity of $v_c = (GMa_0)^{1/4}$ at the galactic outskirts, thus accounting for flat rotation curves without invoking the need for DM. These results can also be arrived at by considering a minimum acceleration corresponding to a minimum gravitational field strength (at the outskirts of galaxies and galaxy clusters), as given by [6,7] in

$$a_{min} = \frac{GM}{r_{max}^2} \tag{2}$$

Here, $a_{min} \approx 10^{-8}$ $\text{cms}^{-2}$ plays the same role as the MOND acceleration $a_0$, below which the Newtonian dynamics is modified, giving rise to the observed galactic dynamics [8,9]. By postulating a minimum possible acceleration, we eliminate the ad hoc nature of the MOND acceleration $(a_0)$. This postulate gives rise to a maximum radius, $r_{max}$ (through Equation (2)) corresponding to the minimum acceleration, i.e., it is the maximum possible size to which a large-scale structure of mass $M$ can grow [10].

Further, using the expression for $r_{max}$ (from Equation (2)) in the usual relation for the velocity of stars in the galactic outskirts, we have

$$v_c^2 = \frac{GM}{r_{max}} = \frac{GM}{\sqrt{\frac{GM}{a_{min}}}} \tag{3}$$

From Equation (3), using Equation (2) we obtain

$$v_c = (GMa_{min})^{1/4} \tag{4}$$

This is same as the constant velocity in the galactic outskirts, as proposed by MOND with the minimum acceleration, $a_{min}$, here playing the role of MOND acceleration, $a_0$. Equation (4) is also consistent with the Tully Fisher relation [11]. Hence, this postulate of the minimal acceleration (field strength) leads to the same results as MOND (similar to the example seen in Equation (4)).

The modification of Newtonian dynamics is phenomenological at its best and works well in accounting for the dynamics of galaxies and galaxy clusters [12]. However, a relativistic MOND theory is needed to predict cosmological effects such as gravitational lensing. The third peak in the acoustic power spectrum serves as a test for the effect that MOND might have on the CMB [13].

The TeVeS, a relativistic MOND theory derived from the action principle, consists of a scalar field, a four-vector field, and a free function. It was successful in predicting gravitational lensing without invoking DM; it also passes the solar tests of GR and does not cause superluminal propagation [14]. Although, the theory made no predictions for the effect of MOND on CMB. A new relativistic MOND theory (RMOND) similar to TeVeS with additional degrees of freedom has proven to be consistent with the observed CMB and matter spectra on linear cosmological scales [15].

## 2. Baryonic Matter Abundance

### *2.1. Mass–Radius Relation*

It was earlier pointed out [16–18] that for a wide range of large-scale cosmic structures, such as galaxies, galaxy clusters, superclusters, etc., the gravitational binding self-energy density $\frac{GM^2}{8\pi R^4}$ should at least be equal to the background repulsive dark energy density (caused by the $\Lambda$ term), i.e., $\rho_{DE} = \frac{\Lambda c^4}{8\pi G}$. Thus, giving rise to,

$$\frac{GM^2}{8\pi R^4} = \frac{\Lambda c^4}{8\pi G} \tag{5}$$

where $M$ is the total mass of the large-scale structure, $R$ is its observed size, and $\Lambda \left(= 10^{-56}\ \text{cm}^{-2}\right)$ is the cosmological constant term (as implied by the observations).

Equation (5) thus implies a mass–radius relation of the type [16–18]

$$\frac{M}{R^2} = \frac{c^2}{G}\sqrt{\Lambda} \approx 1\ \text{gcm}^{-2} \tag{6}$$

The universality of Equation (6) was pointed out earlier [16], holding true for a wide range of structures from globular clusters to galaxies (both early and late) as well as galaxy clusters up to the Hubble volume.

From Equation (2), the mass–radius relation also takes the form,

$$\frac{M}{R^2} = \frac{a_{min}}{G} \tag{7}$$

For the Universe as a whole, a minimal acceleration $a_0 = 10^{-8}$ cms$^{-2}$ corresponding to a minimal gravitational field strength provides a mass–radius relation value of 1/6 gcm$^{-2}$, which is five times lesser than that expected (Equation (6)), thus, implying a need for an additional five times more mass.

### 2.2. The Eddington Luminosity

The Eddington luminosity or the Eddington limit is the maximum luminosity a body can achieve when there is a balance between the force of radiation acting outward and the gravitational force acting inward, i.e., the body is in a state of hydrostatic equilibrium [19]. The Eddington luminosity is given as follows,

$$L_{max} = \frac{4\pi G M m_p c}{\sigma_T} \tag{8}$$

where $M$ is the mass of the accreting object, $m_p$ is the mass of a proton, and $\sigma_T$ $(= 6.65 \times 10^{-25}\ \text{cm}^2)$ is the Thomson cross-section$\left(\sigma_T = \frac{8\pi}{3}\left(\frac{\alpha\hbar}{mc^2}\right)^2\right)$.

The maximum radiation force from Equation (8) is thus,

$$F_{max} = \frac{4\pi G M m_p}{\sigma_T} \tag{9}$$

Equation (9) corresponds to a maximum acceleration of,

$$a_{max} = \frac{F_{max}}{M} = \frac{4\pi G m_p}{\sigma_T} \approx 1.77 \times 10^{-7} \text{cms}^{-2} \tag{10}$$

This is the maximal acceleration that can be produced by the outward radiation pressure force corresponding to the maximum luminosity that the total baryonic mass in the Universe can reach while maintaining a balance between the radiation pressure force acting outward and the inward gravitational force. As inferred from Equation (10), this maximal acceleration interestingly turns out to be an order greater in magnitude than the minimum gravitational acceleration (Equation (1)).

In earlier work, it was noted that the field equations of general relativity are implied by a maximal force given by [20],

$$F_{max} = \frac{c^4}{G} \approx 1.2 \times 10^{49} \text{gcms}^{-2} \tag{11}$$

This is analogous to the way special relativity is implied by a maximal speed, as given by $c$.

Thereby, for the same force (Equation (11)) present over cosmic scales, the acceleration provided by Equation (1), which is ten times that provided by Equation (10), would imply that the baryonic mass is correspondingly lower by an order of magnitude. Thus, the total baryonic mass is about ten times less than the observed total mass of the Universe.

Additionally, Equation (11) would imply a limiting luminosity of [20,21]

$$\frac{c^5}{G} = 3.72 \times 10^{59}\ \text{erg s}^{-1} \tag{12}$$

All baryons undergoing nuclear reactions cannot exceed Eddington luminosity (Equation (8)). Therefore, the combined Eddington luminosity of all the baryons should be limited by Equation (12). This limits the mass as,

$$\sum M = \frac{\sigma_T c^4}{4\pi G^2 m_p} = 6 \times 10^{54}\ \text{g} \tag{13}$$

This yields the baryonic density as

$$\rho_m = \frac{\sigma_T c {H_0}^3}{8\pi^3 G^2 m_p} = 3 \times 10^{-31}\ \text{gcm}^{-3} \tag{14}$$

that is, around 3% of the critical density of the Universe $\left(10^{-29}\ \text{gcm}^{-3}\right)$. Thus, again indicating that baryonic matter constitutes less than five percent of the total energy density of the Universe.

## 3. Implications from the Modification of Newtonian Gravity (MONG)

In usual Newtonian gravity, the above results would indicate the need for non-baryonic matter. This is not the case in this model, as these physical phenomena (Section 2) can be accounted for by the modification of Newtonian gravity (MONG) [7,19,22,23]. In MONG, we consider an additional gravitational self-energy term in Poisson's equation, providing a logarithmic term in the solution. With this modification (including the DE term), we have the following:

$$\nabla^2 \phi = 4\pi G\rho + K(\nabla\phi)^2 + \Lambda c^2 \tag{15}$$

where $\phi\left(= \frac{GM}{r}\right)$ is the usual gravitational potential and the constant $K\left(\approx \frac{G^2}{c^2}\right)$. $K(\nabla\phi)^2$ is the gravitational self-energy density. For a typical galaxy, such as the Milky Way, beyond a distance of $r_c = 10kpc$ from the galactic center, where the matter density is small [23], the gravitational self-energy term begins to dominate.

Thus, Equation (15) now takes the form (neglecting the dark energy term $\Lambda$)

$$\nabla^2 \phi - K(\nabla\phi)^2 = 0 \tag{16}$$

The solution of Equation (13) yields

$$\phi = K' \ln \frac{r}{r_c} \tag{17}$$

where $K' \approx \frac{GM}{r_{max}}$ is a constant. This provides a force of the form [7],

$$F = \frac{K''}{r} \tag{18}$$

where $K'' = (GMa_{min})^{1/2}$ is also a constant.

The Milky Way, with a size of $R = 5 \times 10^{22}$ cm and a luminous mass of $M = 2.9 \times 10^{44}$g and $r_c = 5kpc \approx 1.5 \times 10^{22}$ cm, corresponds to a Newtonian gravitational force (per unit mass) of,

$$F = \frac{GM}{R^2} \approx 7.7 \times 10^{-9}\ \text{gcms}^{-2} \tag{19}$$

MONG predicts the dominance of the gravitational self-energy term beyond the distance $r_c$, and the net gravitational force takes the form as shown in Equation (18). This yields a value of $3.5 \times 10^{-8}$ gcms$^{-2}$, i.e., an order greater in magnitude than the usual Newtonian force. This additional force from MONG obviates the need for dark matter (which in the usual picture is about an order of magnitude greater than the luminous matter), which is required in the $\Lambda CDM$ model.

The gravitational self-energy term in MONG provides the required gravitational force accounting for the dynamics of galaxies that are usually attributed to dark matter in the usual model. Dark matter is expected to constitute more than half the mass of typical late-type galaxies, such as the Milky Way [9,24], whereas a recent analysis of the rotation curves of early-type galaxies found that dark matter does not dominate galaxies in the early Universe [25]. This is in agreement with the MONG estimates, as shown in Table 1. The gravitational force is an order (or more) greater in magnitude for late-type galaxies.

**Table 1.** Comparison of the Newtonian gravitational force to that from MONG for galaxies.

| Galaxy | Luminous Mass (g) | Newtonian Gravitational Force (N) | Gravitational Force from MONG (N) |
|---|---|---|---|
| *Andromeda* | $2.4 \times 10^{44}$ | $1.48 \times 10^{-9}$ | $3.8 \times 10^{-8}$ |
| *Triangulum* | $9 \times 10^{42}$ | $7.5 \times 10^{-10}$ | $2.73 \times 10^{-9}$ |
| *GN z-11* | $1.9 \times 10^{41}$ | $1.61 \times 10^{-9}$ | $4.5 \times 10^{-9}$ |
| *Messier 81* | $9 \times 10^{42}$ | $3.2 \times 10^{-10}$ | $1.8 \times 10^{-9}$ |
| *Pinwheel* | $1.9 \times 10^{44}$ | $1.96 \times 10^{-9}$ | $4.4 \times 10^{-9}$ |
| *Black eye* | $7.9 \times 10^{40}$ | $4.8 \times 10^{-12}$ | $2.9 \times 10^{-10}$ |
| *Messier 63* | $2.2 \times 10^{43}$ | $6.8 \times 10^{-10}$ | $2.62 \times 10^{-9}$ |
| *Messier 81* | $9.9 \times 10^{42}$ | $2.2 \times 10^{-9}$ | $5 \times 10^{-9}$ |
| *NGC 300* | $6.9 \times 10^{42}$ | $2.4 \times 10^{-10}$ | $1.5 \times 10^{-9}$ |
| *Sculptor* | $1.98 \times 10^{43}$ | $7.4 \times 10^{-10}$ | $2.7 \times 10^{-9}$ |
| *EGS-zs8-1* | $1.59 \times 10^{42}$ | $5.3 \times 10^{-10}$ | $2.3 \times 10^{-9}$ |

For GN z-11, the oldest galaxy detected in the observable Universe, the gravitational force from MONG is just three times greater than the Newtonian force. Additionally, we find that MONG provides a gravitational force that is two orders in magnitude greater than the Newtonian force for the Black eye galaxy. This can be attributed to the fact that the Black eye galaxy is a type 2 Seyfert galaxy with an active supermassive black hole at the center. Active galaxies are more luminous and hence require a greater gravitational force to balance the outward radiation pressure force. A recent work discovered that a scalar field coupled to a fluid could also lead to a form of extended Newtonian gravity [26].

## 4. Implications for Hot Gas in Clusters

The baryons in galaxies and galaxy clusters either quickly cool down, forming stars, or aggregate into very hot clouds of gas between the galaxies in clusters [27,28]. Extended emissions in the X-ray observations of clusters of galaxies indicate the presence of hot gases distributed throughout the cluster volume [29]. These hot gases correspond to a temperature of the order of $10^7$ K or even higher. The pressure of the hot gases is balanced by the gravitational pull of the total mass in the galaxy. However, the mass of all the visible matter in the galaxy cluster does not provide the required potential to hold the hot gases in place. This led to the conclusion that the additional gravitational force required to balance the pressure of hot gases is provided by dark matter. Thereby, galaxies must contain five times more mass (dark matter) than what is visible, thus providing the required gravitational potential to hold the hot gases within the cluster.

Alternatively, the presence of hot gases in clusters can be explained without invoking dark matter through the use of MONG. At the regions in the outskirts of galaxy clusters, where hot gases are observed, the gravitational self-energy term indicated in Equation (15) is more dominant. Thus, the potential increases logarithmically (Equation (17)) with distance, providing the required gravitational potential to hold the gases within the cluster (for example, for $r$ of the order of 10 $r_c$ this implies an order of about a three times increase in force). This obviates the need for DM within the clusters.

## 5. Conclusions

The physical implications of Eddington luminosity and the mass–radius relation for (galaxies and galaxy clusters) provides a relative abundance of baryonic matter in the Universe, which is similar to that established through observations. Baryonic matter makes up for less than 15% of the matter density in the Universe. This need for an additional 85% of matter is attributed to the presence of non-baryonic invisible matter (DM) in the standard model. However, the existence of dark matter is yet to be confirmed in dark matter detection experiments, which have been running for decades. In this work, we explored the implications of the Modifications to Newtonian Dynamics (MOND) as an alternative to dark matter.

In MONG, we consider an additional gravitational self-energy term in Poisson's equation, providing a logarithmic term in the solution. For a typical galaxy, such as the Milky Way, beyond a distance of about 10kpc from the galactic center, the gravitational self-energy term begins to dominate, providing a force that increases logarithmically with distance, thus accounting for the dynamics without requiring dark matter. The Newtonian gravitational force is compared to that obtained from MONG for various galaxy types, which is in accordance with the observations (with MONG replacing DM). This argument can similarly be extended to larger scales, such as that of galaxy clusters and superclusters.

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