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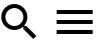
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# A Simple Model for Explaining Galaxy Rotation Curves

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A new simple expression for the circular velocity of spiral galaxies is proposed and tested against HI Nearby Galaxy Survey (THINGS) data set. Its accuracy is compared with the one coming from MOND.

**Keywords:** rotation curves (</search?q=rotation+curves>); spiral galaxies (</search?q=spiral+galaxies>); circular velocity (</search?q=circular+velocity>); THINGS (</search?q=THINGS>); MOND (</search?q=MOND>)

## 1. Introduction

The current Standard Cosmological Model, the so-called  $\Lambda$ CDM model [1,2], together with astronomical observations, indicates that there is about 30% of dust matter which we know exists. From it we are able to detect only 20% which is baryonic described by the Standard Model of particle physics. The rest of it is so-called Dark Matter [3,4,5,6] which is supposed to explain the flatness of rotational galaxies' curves [7,8,9,10,11].

Nowadays, there are two main competing ideas for explaining the Dark Matter problem. The first one consists in modifying the geometric part of the gravitational field equations (see e.g., [12,13,14,15]) while the other one introduces weakly interacting particles which have failed to be detected [16]. Despite this, it is also believed that these two ideas do not contradict each other and could be combined together in some future successful theory.

If Dark Matter exists, it interacts only gravitationally with visible parts of our universe, and it seems to also have an effect on the large scale structure of our Universe [17,18]. There are some models which have faced the problem of this unknown ingredient. The famous one is called Modified Newtonian Dynamics (MOND) [19,20,21,22,23,24,25]—it has already predicted many galactic phenomena and this is why it is very popular among astrophysicists. It has already a relativistic version: the so-called Tensor/Vector/Scalar (TeVeS) theory of gravity [26,27]. The MOND result is also obtained when one considers an effect caused by a reaction of dark energy to the presence of baryonic particles [28,29]. Another approach is to consider Extended Theories of Gravity (ETGs) in which one modifies the geometric part of the field equations [30,31,32]. There were also attempts to obtain MOND result from ETGs, see for example [33,34,35,36,37,38]. The Weyl conformal gravity [39,40,41] is another interesting proposal for explaining rotation curves. Moreover, we would also like to mention the existence of a model based on large scale renormalization group effects and a quantum effective action [42,43,44]. In this work we will not consider any concrete theory of gravitation from which we propose the equation ruling the motion of galactic stars. Starting from the standard form of the

geodesic equation, a formula for the rotational velocity will be derived. We will also present how our simple model matches the astrophysical data and how it possesses some similarities to the ones appearing in the literature. At the end we will draw our conclusions. The metric signature convention is  $(-, +, +, +)$ .

## 2. Proposed Model

The standard expression of the quadratic velocity for a star moving on a circular trajectory around the galactic center is simply obtained from the GR in the weak field and small velocity approximations. One assumes that the orbit of a star in a galaxy is circular which is in a good agreement with astronomical observations [45]. Thus the relation between the centripetal acceleration and the velocity is simply:

$$a = -\frac{v^2}{r}. \quad (1)$$

A test particle as we treat a single star in our considerations satisfies the geodesic equation

$$\frac{d^2 x^\mu}{ds^2} + \Gamma_{\nu\sigma}^\mu \frac{dx^\nu}{ds} \frac{dx^\sigma}{ds} = 0. \quad (2)$$

Although the velocity of stars moving around the galactic center is very high, when compared with the speed of light, it turns out that they are still much smaller so we deal with the condition  $v \ll c$ . It means that in the spherical-symmetric parametrization the velocities satisfy

$$v^i = \frac{dr}{dt}, r \frac{d\theta}{dt}, r \sin \theta \frac{d\varphi}{dt} \ll \frac{dx^0}{dt}, \quad (3)$$

where  $x^0 = ct$ . Taking into account Equation (3) and considering the weak field limit of Equation (2) together with  $\Gamma_{00}^0 = 0$  (static spacetime), we obtain

$$\frac{d^2 x^r}{dt^2} = -c^2 \Gamma_{00}^r. \quad (4)$$

Inserting Equation (4) into (1) one gets

$$v^2(r) = rc^2 \Gamma_{00}^r = r \frac{d\Phi(r)}{dr} \quad (5)$$

with  $\Phi(r)$  being a Newtonian potential (see for example [46]) such that finally we have

$$v^2(r) = \frac{GM}{r} \quad (6)$$

where  $G$  is gravitational constant while the mass  $M$  is usually assumed to be  $r$ -dependent, that is, one deals with some matter distribution depending on a concrete model. Let us assume the following simple distribution of mass in a galaxy [47]





$$M(r) = M_0 \sqrt{\frac{R_0}{r_c} \frac{r}{r + r_c}}^{3\beta} \quad (7)$$

with  $M_0$  the total galaxy mass,  $r_c$  the core radius and  $R_0$  the observed scale length of the galaxy. The matter distribution in Equation (7) without the term containing the square root was also used in Reference [48]. Since the GR prediction on the shapes of galaxies' curves coming from (6) failed against the observation data, one looks for some modification. The first one which appears in one's mind is to consider a bit more complicated mass distribution which can also include Dark Matter halo in his form as well as different galaxy structure, for example disk, or other shapes.

We would like to perform a bit of a different approach, that is, let us modify the geometry part by, for example, considering effective quantities that could be obtained from Extended Theories of Gravity. There are many works following this approach which inspired us to examine a below toy model. The most interesting ones which do not assume the existence of any Dark Matter according to the authors are the following:

- The Modified Newtonian Dynamics (MOND) [22] (see also similar result in [49] and reviews in [19,24,25,38]). It is the most spread modification among astronomers since it is very simple, does not include any exotic ingredients (Dark Matter) and the most important, it is in good agreement with observations. The MOND velocity is given by

$$v^2(r) = \frac{GM}{r} \frac{1}{\sqrt{2}} \left( 1 + \sqrt{1 + r^4 \frac{2a_0^2}{GM}} \right)^{1/2} \quad (8)$$

where  $a_0 \approx 1.2 \times 10^{-8} \text{ ms}^{-2}$  is the critical acceleration. Equation (8) is obtained from the Milgrom's acceleration formula

$$a = \frac{MG}{r^2} \mu \left( \frac{MG}{r^2 a_0} \right) \quad (9)$$

using the standard interpolation function

$$\mu(x) = \frac{x}{\sqrt{1 + x^2}} \quad (10)$$

In the limit  $a_{Newt} \gg a_0$ , the MOND formalism gives asymptotic constant velocities

$$v_c^2 = \sqrt{a_0 GM}. \quad (11)$$



- Coming from  $f(R)$  gravity (metric formalism) examined by [32,50]. Here, they used the ansatz  $f(R) \sim R^n$ , to obtain:

$$v^2(r) = \frac{GM}{2r} \left[ 1 + (1 - \beta) \frac{r}{r_c} \right] \quad (12)$$

where  $\beta$  is a function of the slope  $n$  of the Lagrangian while  $r_c$  is a scale length depending on gravitational system properties.

- Given by Scalar-Vector-Tensor Gravity [27,48] which is in very good agreement with the RC Milky Way data

$$v^2(r) = \frac{GM}{r} \left[ 1 + \alpha - \alpha(1 + \mu r)e^{-\mu r} \right] \quad (13)$$

where the two free parameters allow the fitting of galaxy rotation curves.

- Our previous result [47], coming from Starobinsky model [51]  $f(\hat{R}) = \hat{R} + \gamma \hat{R}^2$  considered in Palatini formalism which is the simplest example of EPS interpretation [52]

$$v^2 \approx \frac{GM(r)}{r} \left[ 1 + \frac{2GM(r)}{c^2 r} - \frac{2\pi\kappa\gamma c^2 r^3 \rho^2}{M(r)(1 + 2\kappa\gamma c^2 \rho)^2} \right] \quad (14)$$

where we assumed the order of  $\gamma$  as  $10^{-10}$  taken from cosmological considerations [53],  $\rho$  is energy density obtained from mass distribution provided by the model and (7), see the details in [47].

We immediately observe that all these modifications coming from different models of gravity possess a feature which can be simply written as

$$v^2(r) = \frac{GM}{r} \left[ 1 + A(r) \right] \quad (15)$$

where the unknown function  $A(r)$  depends on the radial coordinate and some parameters. In this manner, the function  $A(r)$  is treated as a deviation from the Newtonian limit of General Relativity.

Our task now is to find a suitable function  $A(r)$  which takes into account and reproduces the observed flatness of galaxy rotation curves. Moreover, at short distances (at least the size of the Solar System) the velocity from Equation (15) should have as a limit the Newtonian result  $v^2(r) = GM / r$ . This imposes some constraints on the function  $A(r)$ .

### 3. A Particular Example

We have seen in the previous section that there are many alternatives to General Relativity which possess extra terms that improve the behavior of the galaxy curves. Moreover, many of them can have the same weak field limit producing the same result (15). Thus, one can explain the observed galaxy rotation curves using the Equation (15) without the assumption on the



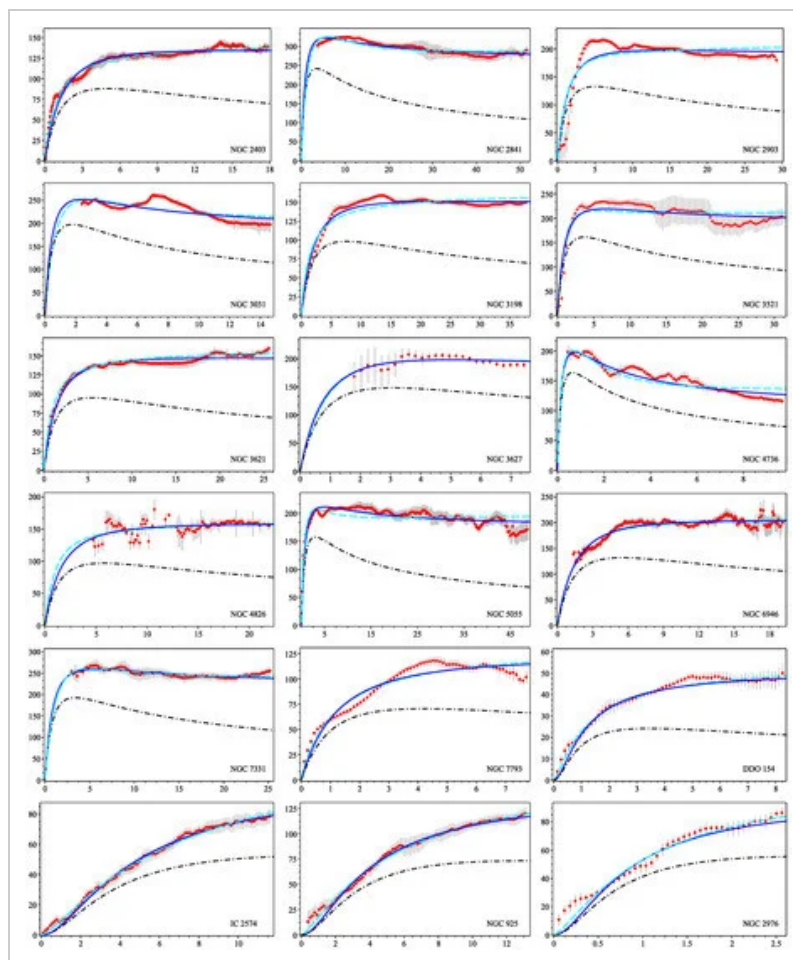
existence of Dark Matter.

In this section we would like to propose a model for fitting the galaxy rotation curves data observed astronomically. As we will see, the model fits quite well the data set of galaxies obtained from THINGS: The HI Nearby Galaxy Survey catalogue [54,55], on which our analysis is performed.

A very simple model that fits well the data (as can be seen from **Figure 1** and **Figure 2**) is obtained by choosing

$$A(r) = b \frac{r + r_0}{r_0} \quad (16)$$

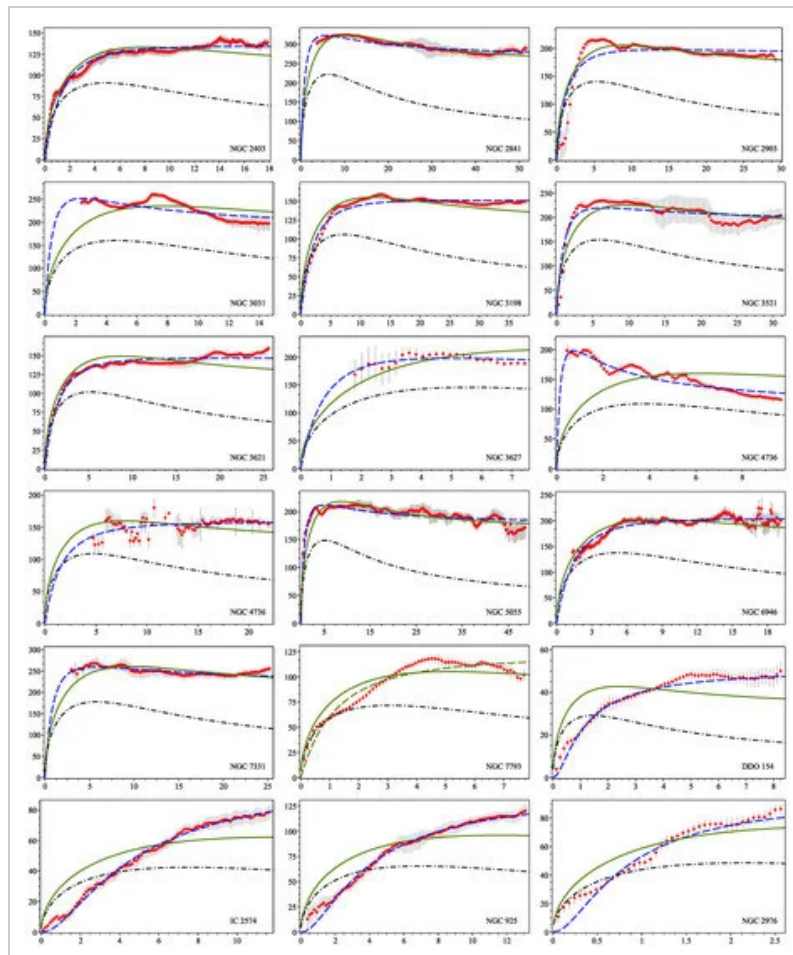
where  $b$  and  $r_0$  are two parameters. The idea of including additionally  $1/r$  term in the gravitational force without or with the Yukawa potential, which improves the behaviour of the theoretically obtained curves, was already discussed in [56,57,58,59].







**Figure 1.** (color online) Rotational velocities in km/s ( $y$  axis) at a certain distance in kpc ( $x$  axis) from the center of the galaxy. The blue curves RC are obtained from the parametric fit of Equation (19) in the case of 18 THINGS galaxies. The properties of the galaxies in the sample can be found in Table I from Reference [55]. The full (blue) curve are the rotation curves obtained using Equation (19); the (red) full circles are the observed data points where the vertical (grey) lines represent the error bars; the contribution due to the Newtonian term is given by the dash-dotted (black) lines, while the dashed (cyan) lines give the MOND rotation curves. The numerical values resulted from the fits are given in **Table 1**.



**Figure 2.** (color online) Rotational velocities in km/s ( $y$  axis) at a certain distance in kpc ( $x$  axis) from the center of the galaxy. The blue curves RC are obtained from the parametric fit of Equation (19) in the case of HSB THINGS galaxies. The full (green) curve is the rotation curves obtained using the spherical mass distribution (21); the (red) full circles are the observed data points where the vertical (grey) lines represent the error bars; the contribution due to the Newtonian term is given by the dash-dotted (black) lines, while the dashed (blue) lines give rotation curves obtained using the mass distribution in Equation (21). The numerical values resulted from the fits are given in **Table 2**.



**Table 1.** Best fit results according to Equation (19) using the parametric mass distribution Equation (7). These numerical values correspond to rotation curves presented in Figure 1. Column (1) name of galaxy; Column (2) distance; Column (3) measured scale length of the galaxy; Column (4) base ten logarithm of total gas mass given by  $M_{gas} = 4/3 M_{HI}$ , with the  $M_{HI}$  data taken from [55]; Column (5) galaxy luminosity in the B-band calculated from [55]; Column (6) base ten logarithm of the predicted stellar mass  $M_*$  of the galaxy (obtained by subtracting  $M_{gas}$  from the best-fit results for the total mass  $M_0$ ); Column (7) the predicted core radius  $r_c$ ; Column (8) reduced  $\chi_r^2$ ; Column (9) the stellar mass-to-light ratio calculated by subtracting the mass of the gas from the total mass and then dividing it by the B-band luminosity; Column (10) base ten logarithm of MOND predicted mass of the galaxy; Column (11) the MOND predicted core radius  $r_c$ ; Column (12) MOND reduced  $\chi_r^2$ ; and Column (13) the MOND stellar mass-to-light ratio.



**Table 2.** Best fitting results using Equations (17) and (21). The corresponding rotation curves are given in Figure 2. Column (1) is the name of the galaxy; Column (2) the galaxy type; Column (3) gives best-fit results for the predicted galaxy stellar mass; Column (4) gives the values of reduced  $\chi_r^2$ ; and Column (5) gives the stellar mass-to-light ratio.



Inserting the Equation (16) into the velocity Formula (15) we obtain

$$v^2(r) = \frac{GM}{r} \left( 1 + b \right) + \frac{r}{r_0}. \quad (17)$$

In the non-relativistic limit, the circular velocity and the gravitational potential are related through the usual formula  $v^2(r) = r \frac{d\Phi}{dr}$ , from which it follows immediately that

$$\Phi(r) = -\frac{GM}{r} \left( 1 + b \right) - \frac{r}{r_0} \ln \frac{r}{r_0}. \quad (18)$$

The dependence on  $\ln(r/r_0)$  in the potential was also reported in References

[42,43,44,49,60]. Moreover, we observe that in the limit  $b \rightarrow 0$  both Equations (17) and (18) reduce to their usual Newtonian expressions. It should also be mentioned that the considered form (17) can cause problems with lensing effect if one finds out the relativistic version of the model. There is a proposed mechanism in [61] which allows to interpolate between the short and long distance ranges in order to avoid the divergence of the effective mass when  $r \rightarrow \infty$ . It also takes into account the necessity of rescaling the gravitational mass (which appears because of the constant  $b$ ) in order to save the desired properties of the model when we consider it in the case of the Solar System.

Using the matter distribution (7) and identifying the parameter  $r_0$  contained in the Equation (17) with the galaxy scale length  $R_0$ , the final rotational velocity of stars moving in circular orbits is

$$v^2(r) = \frac{GM_0}{r} \sqrt{\frac{R_0}{r_c} \frac{r}{r+r_c}}^{3\beta} \left(1 + b\right) + \frac{r}{R_0} \quad (19)$$

One can immediately deduce an important feature of the above formula, namely that in the limit of large radii we obtain flat rotation curves, similar to what happens in MOND theories [22,23,24] (see also Equation (11) above)

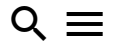
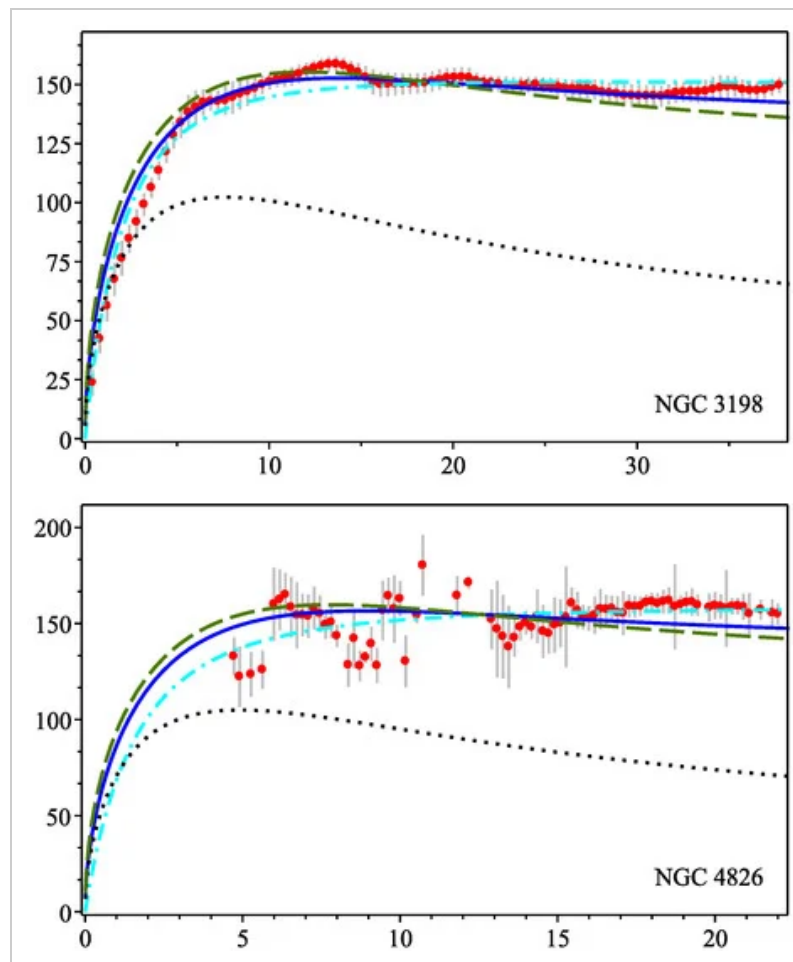
$$v_0 = \sqrt{\frac{GMb}{R_0} \frac{R_0}{r_c}}^{3\beta/2} \quad (20)$$

From the analysis of the 18 THINGS galaxies sample we have found  $b = 0.352 \pm 0.08$  to give good fit results for the rotation curves. The plots in **Figure 1** and the best fit results from **Table 1** are obtained using the value  $b = 0.352$ . As in [48] the value  $\beta = 1$  (for HSB galaxies) and  $\beta = 2$  (LSB galaxies) give good fit results. By allowing  $\beta$  to be a free parameter, slightly better fits results can be obtained. In this case a preliminary analysis indicates that  $0.75 < \beta < 1.25$  for HSB galaxies and  $1.9 < \beta < 2.1$  for LSB galaxies. However, in order to keep the free parameters to a minimum we have chosen here to fix the value of  $\beta$ .

If we replace the matter distribution (7) in the Equation (17) with the one coming from the spherical version of the exponential disc profile [45]

$$M(r) = M_0 \left(1 - 1 + \frac{r}{R_0} \exp\left(-\frac{r}{R_0}\right)\right), \quad (21)$$

we can then fit the rotation curves using only  $M/L$  as a free parameter. The resulted predicted values for the stellar mass of the galaxies are given in **Table 2** together with the corresponding rotation curves in **Figure 2**. By combining the mass distributions (7) and (21) a “core-disk” model can be obtained. However, the resulted masses will be much lower that in the cases when the core mass distribution and the disk profile are considered to be independent. In **Figure 3** we can see the resulted rotation curves using the three mass distributions for two galaxies.



**Figure 3.** (color online) Comparison of rotation curves obtained using the “core” mass distribution (7) (**cyan dash-dot curve**), the observed data (**red full circles** with vertical grey lines (error bars)), the disk profile (21) (**green dash curve**) and the “core-disk” mass distribution (**blue solid curve**) together with its Newtonian contribution (**black dotted curve**).

### The Tully-Fisher Relation

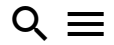
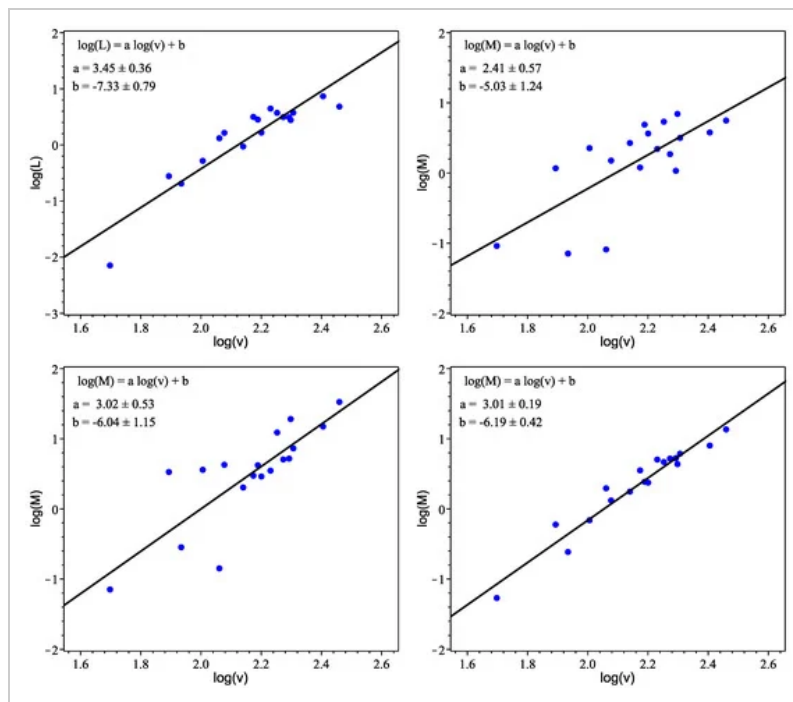
The empirical observational relation between the observed luminosity of a galaxy and the fourth power of the last observed velocity point is known as the Tully-Fisher relation [62]

$$L \propto v_{last}^4, \quad (22)$$

which can be rewritten as

$$\log(M) = a \log(v) + b. \quad (23)$$

In the **Figure 4** we have presented the observational Tully-Fisher relation (top-left panel) together with the fits of the parametric model given by the Equation (17) using the mass distribution (7) in the right-top panel and the spherical version of the exponential disk mass distribution (21) in the right-bottom panel, respectively. The left-bottom panel presents the Tully-Fisher relation coming from MOND mass predictions.



**Figure 4.** (color online) The Tully-Fisher relation. **Left-top panel:** the observed B-band Tully-Fisher relation. Vertical axis gives the base 10 logarithm of the observed luminosity (in units of  $10^{10} L_{\odot}$ , respectively  $10^{10} M_{\odot}$ ) and the horizontal axis is the base 10 logarithm of the last observed velocity (in km/s). **Left-bottom panel:** best fit Tully-Fisher relation parameterized by  $\log(M) = a \log(v) + b$  in the case of MOND. **Right-top panel:** Tully-Fisher best fit for the masses resulted from the parametric model given by Equation (17) using the mass distribution (7), respectively. **Right-bottom panel:** Tully-Fisher relation obtained using the spherical version of the exponential disk mass distribution (21). The value of  $M$  used in the plots is the total mass of a given galaxy:  $M = M_* + M_{gas}$ .

#### 4. Discussion and Conclusions

In the presented paper we have considered the possible explanation of observed galactic rotation curves by the assumption that the observed effect of the flatness can be explained by some alternative theory of gravity which introduces an extra term which we called  $A(r)$ . This term can be treated as a deviation from the Newtonian limit of GR.

Our results are presented in **Table 1** and **Table 2** together with the plots in **Figure 1** and **Figure 2**. Although we would like to consider this contribution like something coming from a slightly different geometry appearing in the modified Einstein field equations, it can be also thought of as some extra field, for example the scalar one which has recently been considered as an agent of the cosmological inflation [63,64,65,66]. This choice for  $A(r)$  in (16) could be explained by considering two conformally related metrics (the GR metric  $g_{\mu\nu}$  and a “dark metric”  $h_{\mu\nu}$ ) as proposed in [47]. However, so far we have not been able to find a suitable metric



$h_{\mu\nu}$ . This means that one needs to know a form of a lagrangian in the case of Palatini gravity in order to know the form of the dark metric.

From now on we shall compare the new phenomenological model proposed in **Section 2** for explaining flat galaxy rotation curves with the widely accepted MOND model.

Let us start analyzing the predictions from **Table 1**. Comparing Column (7) and Column (3) from the **Table 1** we observe that in all galaxies of the sample (excepting NGC4826 and NGC7793) the predicted core radius  $r_c$  is smaller than the galaxy length scale  $R_0$ . The same is true for MOND (excepting galaxies NGC7793, DDO154 and IC2574). The ratio between the predicted MOND mass in Column (10) and the predicted mass in Column (6) is in the interval (0.4, 8.1) such that for 13 out of 18 galaxies the MOND mass is higher.

◀ The stellar mass-to-light ratio  $M/L$  (denoted  $Y_*$ ) is usually estimated in the literature [69,70,71] by using color-to-mass-to-light ratio relations (CMLR) of the type

$$\log Y_*^i = a_i + b_i \cdot color \quad (24)$$

$a, b$  are two parameters and  $i$  is the band of the measured data. Then using the observed luminosity in the corresponding band, an estimate of the stellar mass is obtained. In [70] the authors use CMLR and four stellar population synthesis models [71,72,73,74] to compute the stellar mass for a sample of 40 galaxies, including 13 of the THINGS galaxies used in this paper. Comparing our predicted stellar mass from the **Table 1**, Column (6) with the values from the Table 3 in [70] and/or the values from the Tables 3 and 4 in [54] we have found that for five galaxies the predicted mass in Column (6) is in very good agreement, for seven galaxies the mass is higher, while for four of the galaxies the mass is slightly lower. Looking now at the values of Column (9) in the **Table 1** and Column (5) in the **Table 2** we can say that the values of  $Y_*$  are in agreement with what is expected based on stellar population models [70]. However, using the spherical mass distribution (21) for LSB galaxies does not result in good fits for the rotational curves.

In Column (8) and Column (12) of **Table 1** the values of reduced  $\chi^2$  are presented. These values were computed using the standard definition:  $\chi_r^2 = \chi^2 / (N - n)$ , where  $N$  is the number of observational velocity data points;  $n$  is the number of parameters to be fitted; and

$$\chi^2 = \sum_i^N \frac{V_i^{obs} - V_{model}(R_i)}{error_i}^2 \quad (25)$$

Taking all of the above into account, one arrives to the conclusion that the new model (which does not assume the existence on any type of Dark Matter) proposed in this paper gives very good flat rotation curves fits of the 18 THINGS galaxies in the data sample. Moreover, when compared with MOND, the difference between the two set of fits is small and thus one is not able to say which model is better than the other one for the explanation of the rotation

We had not had any concrete theory in mind when we wanted to check our assumptions on the modification term  $A(r)$ . Since we have been influenced by the results obtained by the others (briefly described in **Section 2**), we wanted to find much simpler modification apart from QMEND which also provides a required shape of the galaxies' curves. Therefore now, when we have shown that observational data does not exclude the obtained result (19), it is stimulating to think about existing theories of gravity.

The proposed model presented in this paper (enclosed in Equation (19)) can be viewed for now as a phenomenological model, until a concise theory of gravity from which it can be derived, will be found or constructed. We started to tackle this task, thus working on a given theory of gravity which produces a simple modification of the quadratic velocity is a topic of our current research.

References

## Author Contributions

All authors contributed to Conceptualization, Methodology and writing the draft of the paper.

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## Conflicts of Interest

The authors declare no conflict of interest.

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Typo setting math: 12%





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Wojnar A, Sporea CA, Borowiec A. A Simple Model for Explaining Galaxy Rotation Curves. *Galaxies*. 2018; 6(3):70. <https://doi.org/10.3390/galaxies6030070>

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Wojnar, Aneta, Ciprian A. Sporea, and Andrzej Borowiec. 2018. "A Simple Model for Explaining Galaxy Rotation Curves" *Galaxies* 6, no. 3: 70. <https://doi.org/10.3390/galaxies6030070>

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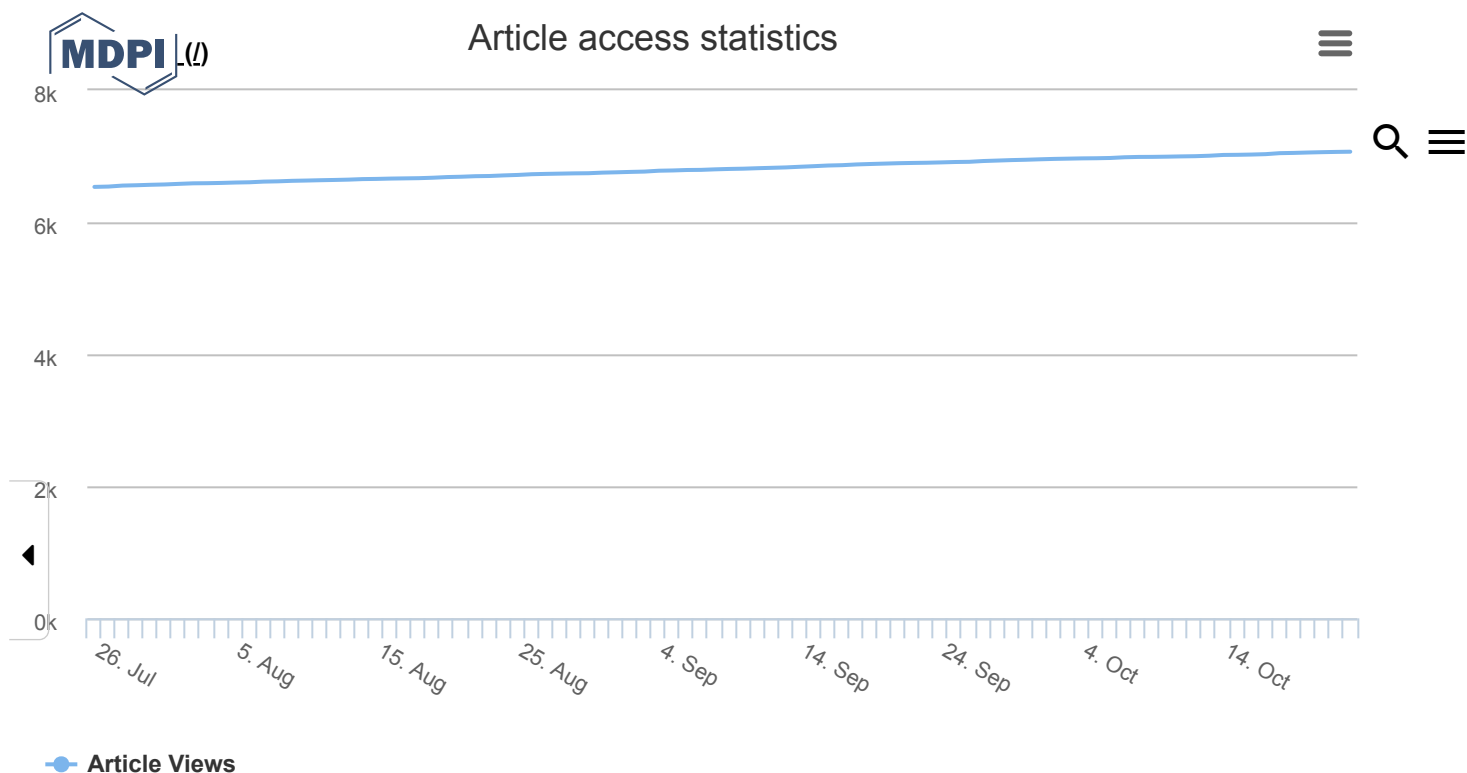
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