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ARTICLE

Dark Matter: Could It Be Vacuum Viscosity?

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Abstract: We test a hypothesis that stars located away from the center of the galaxy, moving under the effect of an emergent viscous drag force perpendicular to their velocities, might exhibit the behavior observed in the rotation curves of the spiral galaxies. We construct a simple model for such an assumption, then by using simple fitting technique, we are able to produce the rotation curves for a sample of 18 spiral galaxies. Results show good agreement with the observed rotation curves. The applicability of our hypothesis suggests that an emergent drag force perpendicular to the velocity of the stars might be the cause of the apparent dark matter effect.

Keywords: Rotation curves, Quantum vacuum, Dark matter.
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Introduction

The problem of the rotation curves of spiral galaxies is well- known since a long time. Classical reviews, which explain the origin of the problem since the work of Zwicky [1], are available [2]. While one would expect the stars and gases in the far parts of the galaxy to behave like being under the effect of the central field of force of the galaxy, thus following Kepler's third law, it is observed that the velocity of these parts of the galaxy is nearly constant and nearly does not change with the distance except for small variations in most cases [3], [4] and [5]. Recently, new studies have extended the range of observation to go up to 200 kpc for our galaxy [6]. Other very recent studies are giving more accurate results for the velocity profile [7] and [8] confirming the nearly constant velocity profile for the stars far from the galactic bulge. This means that the velocities of the stars and gases in this part of the galaxy are lower than what would be expected for a solid disk and are higher than what would be expected from Kepler's third law. This might indicate that the mass of the galaxy is much more than the mass calculated from the observed matter.

The dominant explanation, which was given to this problem, was the assumption of the presence of invisible matter within the galaxies and clusters of galaxies. This excess mass was called *dark matter* and was thought to be within the galactic halo. Dark matter is thought to interact only through its gravitational effect. However, for this assumption to work, most of the dark matter has to be located in the galactic halo. If dark matter is to be clumped in the form of dense planet-sized objects, then one might assume that such objects are in stable orbits around the galaxy, but recent observations of gravitational lensing show that this is not the case [9]. According to observations from the gravitational lensing, dark matter is almost homogeneously distributed within the galactic halo. Several suggestions for other possible candidates of dark matter were presented during

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the past decades, but the preferred one was the so-called weakly interacting massive particles (WIMPs) [10]. For this reason, several projects were launched in an endeavor to detect such WIMPs (for detailed presentations, see [11] and [12]). The last and the most sensitive detector of these was the project of Large Underground Xenon (LUX) detector [13]. Despite all efforts, the LUX project failed to detect any signal, which can be taken confidently to be due to WIMP [14]. The presence of dark matter got support from the analysis of cosmic microwave background radiation, where it was found that the mass density of the universe is larger than the mass density of the observed baryonic matter [15] and [16] (see also the measurements of the Planck project [17] and the results of earlier projects, e.g. [18]).

Another attempt to resolve the problem of the motion of galaxies suggested a modified Newtonian dynamics (MOND) proposal which is claimed to apply in cases of very low acceleration [19]. This is a well-studied proposal [20-23], even though it lacks rigorous theoretical foundations.

The emergent gravity proposal by Erik Verlinde suggests the presence of entropic force showing an elastic effect that causes higher gravity than expected on the basis of standard general relativity [24]. Hence, the higher velocity of the outer parts of the galaxy is not necessarily caused by the presence of larger mass, but by other effects in Verlinde's proposal. However, a recent study has shown that the calculations based on emergent gravity do not explain the rotation curves of the galaxies [25].

Studies concerning the possible interaction of quantum field with baryonic matter are available. Away from any theoretical formulation in this respect, we assume the existence of an emergent viscous force that might result from the interaction of baryonic matter of the moving stars with the virtual quantum states surrounding such stars during their motion. Such emergent force will cause a drag that will cause the stars to have ultimate constant radial velocity.

Interaction of Baryonic Matter with Vacuum

Introducing the vacuum fluctuations into the spacetime induces many effects; the most famous of them in the curved spacetime might be the Casimir effect and the Hawking effect, where particles get created in the vicinity of the event horizon of a black hole. But, in the simplest case, one can assume that vacuum will experience some sort of polarization, which is due to the presence of the massive object, no matter whether it enjoys a horizon or not. Several phenomena where the quantum vacuum interacts with geometry and with baryonic matter and light are thoroughly explained in ref. [26]. It is expected that such a vacuum polarization will certainly induce a concentration of virtual states with density that could be proportional to the distance from the center of the object. Accordingly, a viscous drag is expected to emerge in this case. However, it remains a challenge to show the existence of such a force and show that such an emergent viscosity is inversely proportional to the distance from the center of the massive body. Incidentally, in the Casimir effect, the drag force is proportional to 1/d, where d is the distance from the massive object.

The Model

In this article, we are going to test a proposal that may suggest a new model to explain the rotation curves of spiral galaxies. We assume that the individual stars which are located at the peripheral parts of the galaxy are experiencing a drag force acting upon them radially. Such a force might be produced by some sort of dynamically generated viscous medium and would balance the centripetal acceleration of the star, thus resulting in a terminal velocity. We will not make any attempt here to explain the origin of the assumed drag force or show how it could be generated, but will only try to test such an assumption by fitting the calculated velocity curves of some galaxies to actual observations and see whether they comply with the assumed dynamics. If the fitting results are satisfactory, then the idea might become worthwhile to be considered for further studies in a more profound theoretical context.

As the galaxy rotates, its central part will certainly behave like a disk because of the high density of celestial objects in that region. The outer parts of the galaxy are in motion like any planetary system. This motion can be approximated to be in the state of free fall, as it is taking place under the acceleration of the gravity. As such is the motion of the stars, then once a viscous medium of any sort is assumed to exist, a radial drag force will be generated which will have the mechanical status similar to what happens when a metal ball is dropped into a vessel filled with oil. The viscous drag force will eventually balance the gravitational force and consequently the falling body will attain a terminal velocity. In this model, stars falling under the act of gravity will also attain such a terminal velocity and move with constant speed throughout their path. This proposal may solve the problem of dark matter on the cosmological scale too, since the expansion of the space between large structures in the universe would generate similar effect to that taking place by motion of individual stars of the galaxy.

We assume the presence of a drag force acting radially perpendicular to the velocity vector of the star and balancing the gravitational force acting on it. Therefore, we may equate the emergent viscous force taken here to be described by Stokes' formula with the gravitational force causing the motion of the star. Therefore, we have:

$$F_d = F_g \,. \tag{1}$$

This means that:

$$6\pi a \eta v = \frac{GmM}{r^2}, \tag{2}$$

where *m* is the mass of the star, *M* is the mass of the inner part of the galaxy, η is the coefficient of the emergent vacuum viscosity, *a* is the radius of the star, *r* is the distance of the star measured from the galactic center and *v* is its observed velocity.

Eq. (2) may be written as:

$$6\pi\left(\frac{a}{m}\right)\eta v = \frac{GM}{r^2}.$$

Assuming a circular orbit, the velocity of the star is given by:

$$v^2 = \frac{GM}{r}. \tag{3}$$

Thus, substituting Eq. (3) into Eq. (2), the velocity of the star under this mechanism of the drag force will be given by:

$$v = 6\pi\left(\frac{a}{m}\right)\eta r. \tag{4}$$

Phenomenologically, since *v* is nearly constant, the viscosity coefficient η should be proportional to 1/*r*. Let us, for the sake of argument, assume a more generalized form of the variation of η with the distance r and set:

$$\eta = \frac{C}{B+r}, \tag{5}$$

where B and C are constants that would be determined in this model by fitting the observational data. Accordingly, the velocity of a star located at a distance *r* from the center of the galaxy will be given by:

$$v = 6\pi\left(\frac{a}{m}\right)\frac{Cr}{B+r}. \tag{6}$$

We will try to test this formula by correlating it with actual observations from our galaxy, the Milky Way. In the next step, we will check whether this formula fits well with observational results obtained for the rotation curves of other spiral galaxies.

Calculations and Results

Primarily, we have no idea about the value of the viscosity coefficient η. Let us first evaluate this coefficient empirically using Eq. (4) and the available data about the sun's kinematics given in [26]. The aim is to know the order of magnitude of η in order to obtain an estimation for the viscosity of the medium near the sun. Consequently, we will be able to find the viscosity function along the whole galaxy. To do this, we plot the observed circular velocities v_c of the stars belonging to our galaxy *versus* their distance from the galactic center. The basic data for the sun used in our calculations is the same as that used by ref. [27], with: the mass $M = 1.9889\times10^{30}$ kg, the radius $a = 6.953\times10^{8}$ m, the distance from galactic center $r = 2.57\times10^{20}$ m, $v = 2.5\times10^{5}$ m/s. From this basic data, we can have a rough estimate of the order of magnitude of the viscosity coefficient η; using Eq. (4) we get:

$$\eta = 1.47\times10^{5}\ \text{kg/m.s}\,. \tag{7}$$

Now, in order to find an estimate of the viscosity function along the whole galaxy, we plot the observed circular velocities of the stars *versus* their distances. For this, we use the observational data given in [6] shown in Table 1.

TABLE 1. observational data [6].

r (kpc)	v_c (km/s)
1.61	217.83
2.57	229.58
3.59	223.11
4.51	247.88
5.53	253.14
6.50	270.95
7.56	267.80
8.34	270.52
9.45	235.58
10.50	249.72
11.44	261.96
12.51	284.30
13.53	271.54
14.59	251.43
16.05	320.70
18.64	286.46

The results for the rotation curve of our galaxy are shown in Fig. 1. This distribution of velocities can be taken as a base for a simple fitting out of which we obtain a functional description of the velocity profile. Once we obtain this functional profile, we will have an estimate for a trial function that might be used to check the adherence of the velocity profile of other galaxies to our model.

From the fitting of the rotation curve of our galaxy shown in Fig. 1, we obtain the circular velocity as a function of the radial distance from the galactic center. This is given by:

$$v_c = \frac{286.41148}{0.68598 + r}. \tag{8}$$

Then, using Eq. (6), the dependence of the viscosity coefficient on the radial distance will be given by:

$$\eta(r) = \frac{m}{6\pi a} \frac{286.41148}{0.68598 + r}. \tag{9}$$

To simplify the model, we will take the ratio a/m for the stars to be equal to that of the sun, which is 2.86×10^{21} kg/m. Accordingly, we get:

$$\eta(r) = \frac{4.346\times10^{25}}{2.116\times10^{16} + r}, \tag{10}$$

where now r is in kilometers and η is in kg/km.s.

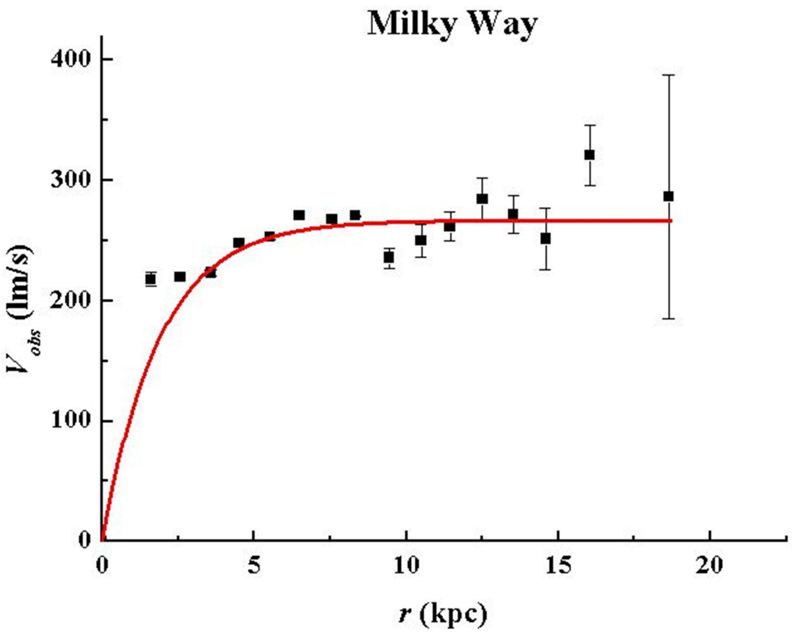

FIG. 1. Fitting of the rotation curve of Milky Way.

Fitting the Rotation Curves of Other Galaxies

Lelli et al. [8] employ the new Spitzer Photometry and Accurate Rotation Curves (SPARC) database. SPARC is a sample of 175 disk galaxies representing all rotationally supported morphological types. It includes near-infrared observations that trace the distribution of stellar mass and 21-cm observations that trace the atomic gas. The 21-cm data also provides velocity fields from which the rotation curves are derived. In some cases, these are supplemented by high spatial resolution observations of ionized interstellar gas. SPARC is the largest galaxy sample to date with spatially resolved data on the distribution of both stars and gas as well as rotation curves for every galaxy.

We have chosen data for 18 spiral galaxies from the SPARC with different distances, as shown in Table 2. These galaxies are chosen from the available set with radii near that of our galaxy. We calculate the viscosity function $\eta(r)$ and then calculate the velocity function for these galaxies. For this purpose, we find that the best fitting function can be expressed in terms of an exponential function as:

$$\mathrm{v}(r) = b(1 - e^{-r/c}), \qquad (11)$$

where b and c are constants that vary from one galaxy to another. Accordingly, the viscosity coefficient function will be given by:

$$\eta(r) = \frac{1}{6\pi}\left(\frac{m}{a}\right)\frac{b(1-e^{-r/c})}{r}. \qquad (12)$$

The constants b and c for the 18 galaxies under consideration are given in the last two columns of Table 2. It is noticeable that the constants b and c in Eq. (11) and Eq. (12) correspond to the terminal velocity at the far rim and the galactic bulge, respectively. This has been found as we compare the values given in Table 2 with the data known about the galaxies. However, this correspondence will be better explained in a model establishing the detailed vacuum fluctuation interaction effect.

We plot the calculated fitting curves against the observational data for the 18 galaxies listed in Table 2, where the square dots stand for the observational data and the fitting is represented by the solid line. It is interesting to note that some curves show excellent fit even better than that obtained for our galaxy shown in Fig. 1. The novelty of our work is the ability to adopt the fitting of the rotation curves of so many galaxies with the identification of two parameters only, the radius of the galactic bulge and the terminal velocity of their far rims.

TABLE 2. data for the 18 spiral galaxies from SPARC.

Galaxy Name	Distance (Mpc)	*b* (km/s)	*c* (kpc)
ESO 563	60.8	312.7	4.85
F-568-3	82.4	122.4	4.86
F-583-1	35.4	86.3	3.37
IC 4202	100.4	247.1	3.02
NGC 1090	37.0	160.0	2.05
NGC 2903	6.60	180.6	0.73
NGC 2998	68.1	203.0	1.20
NGC 3198	13.8	149.0	2.58
NGC 4559	9.00	119.1	2.07
NGC 6015	17.0	152.0	1.27
NGC 6503	6.26	115.0	0.70
UGC 00128	64.5	125.2	4.19
UGC 01230	53.7	103.3	2.22
UGC 03205	50.0	220.0	0.91
UGC 03580	20.7	124.4	1.69
UGC 06786	29.3	211.5	0.23
UGC 11455	78.6	266.0	4.03
UGC 12506	100.6	225.0	2.10
Milky Way	0	266.9	1.9

Figures

Below are the fitting figures that we obtained for the 18 spiral galaxies we have considered in this work.

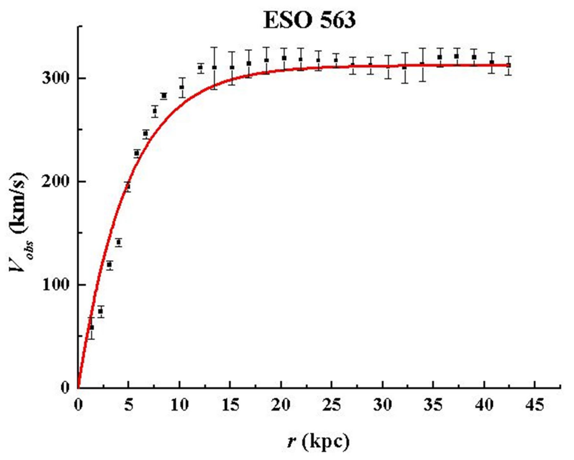

FIG. 2. Fitting results for ESO 563.

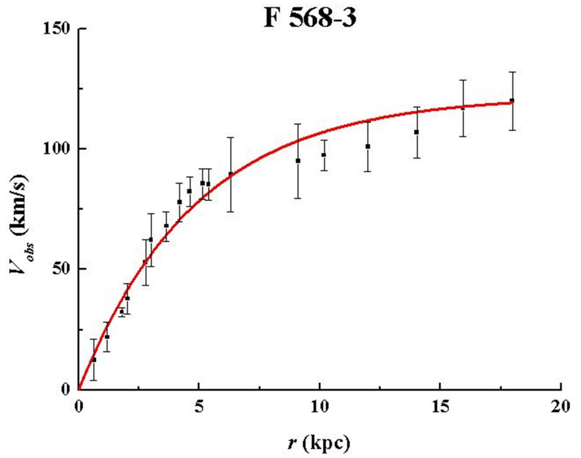

FIG.3. Fitting results for F 568-3.

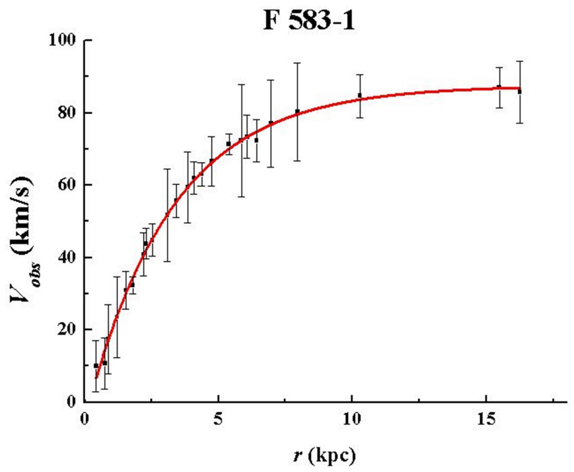

FIG. 4. Fitting results for F 583-1.

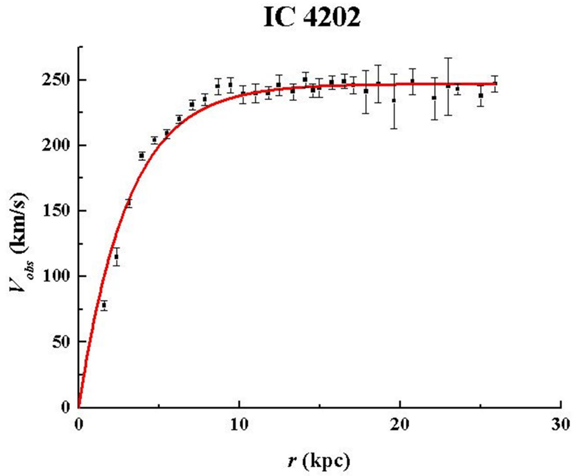

FIG. 5. Fitting results for IC 4202.

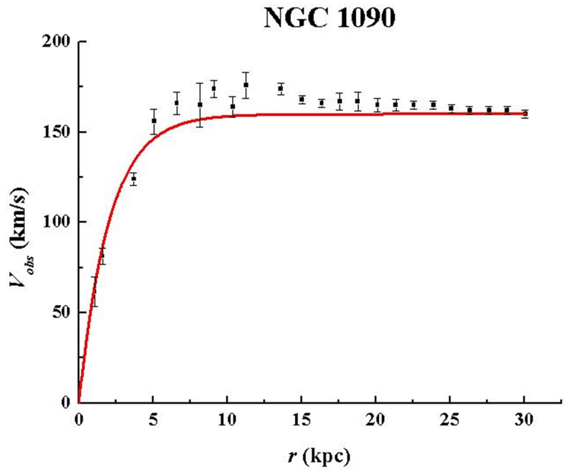

FIG. 6. Fitting results for NGC 1090.

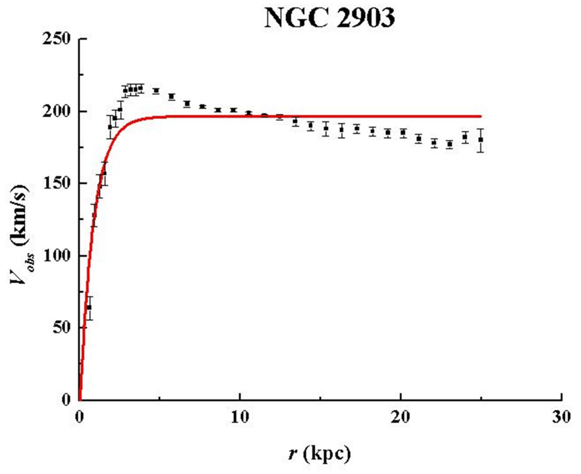

FIG. 7. Fitting results for NGC 2903.

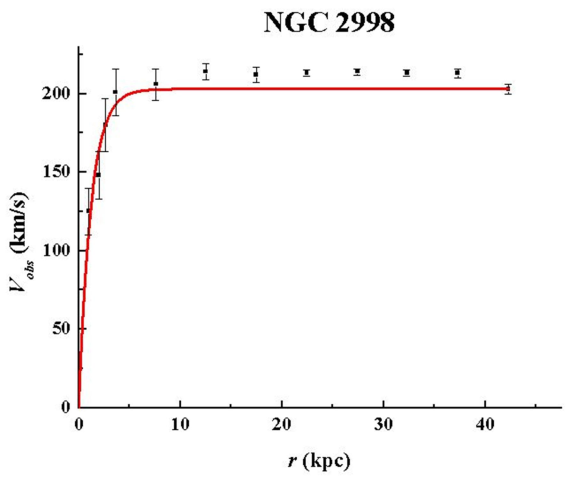

FIG. 8. Fitting results for NGC 2998.

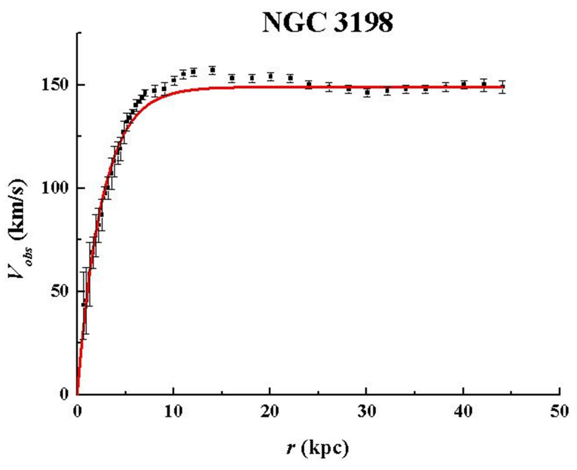

FIG. 9. Fitting results for NGC 3198.

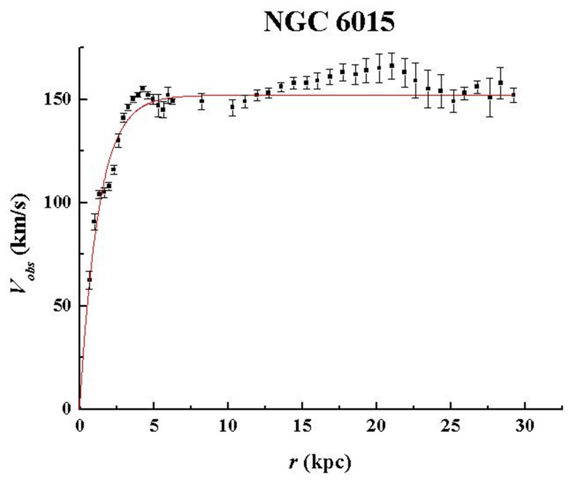

FIG. 10. Fitting results for NGC 6015.

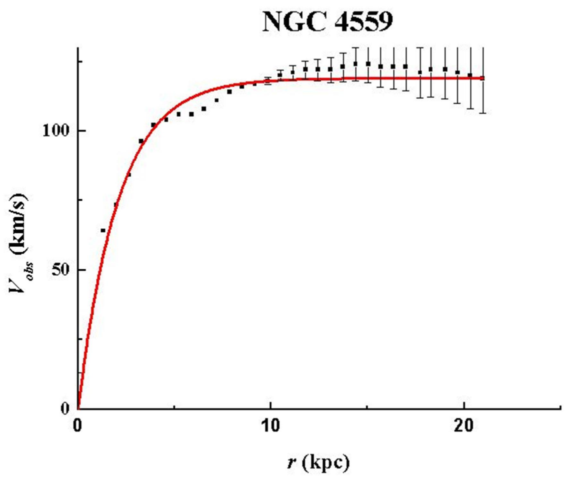

FIG. 11. Fitting results for NGC 4559.

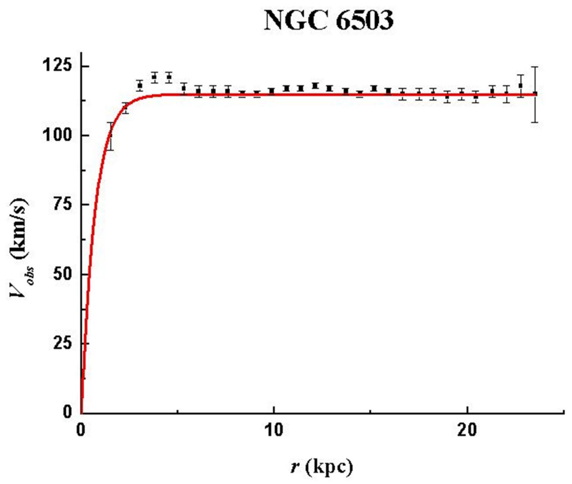

FIG. 12. Fitting results for NGC 6503.

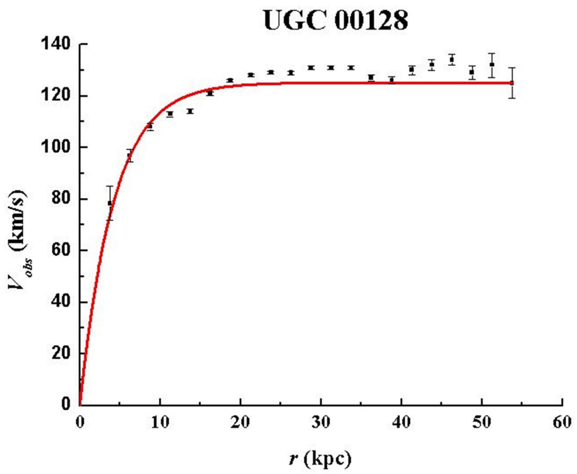

FIG. 13. Fitting results for UGC 00128.

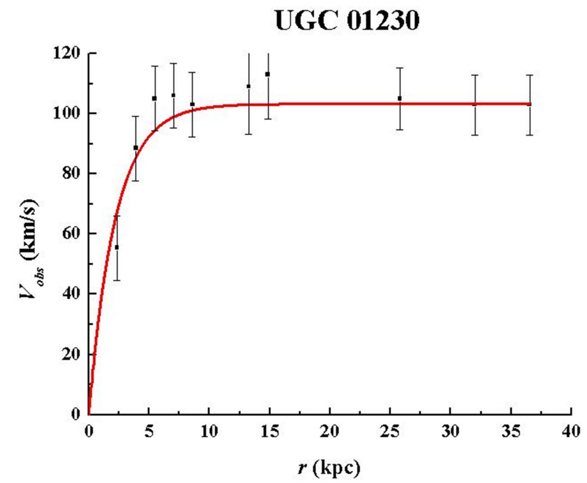

FIG. 14. Fitting results for UGC 01230.

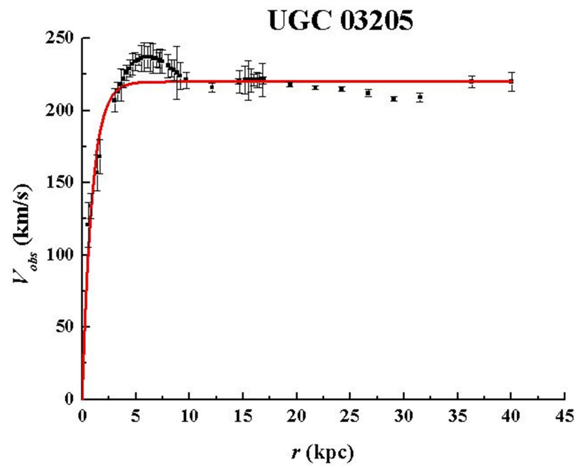

FIG. 15. Fitting results for UGC 03205.

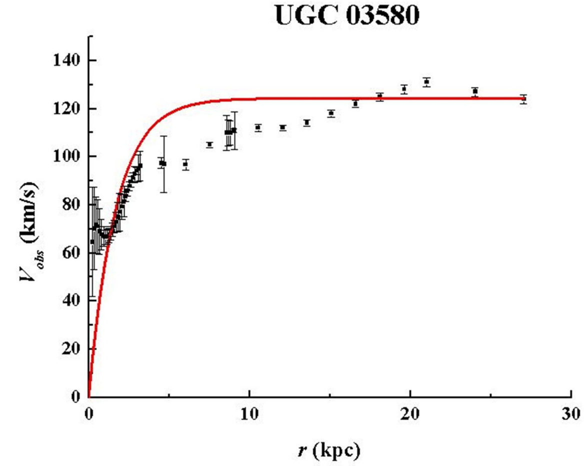

FIG. 16. Fitting results for UGC 03580.

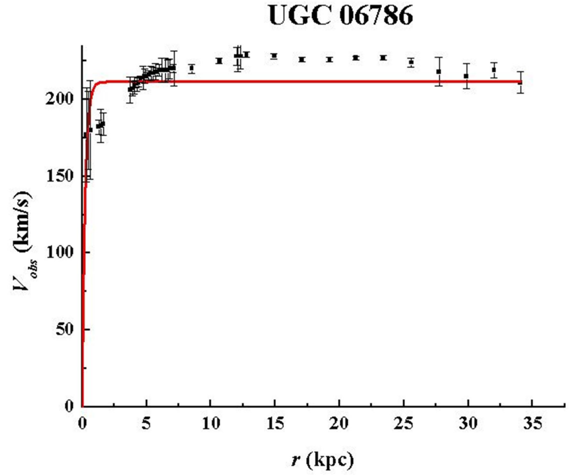

FIG. 17. Fitting results for UGC 06789.

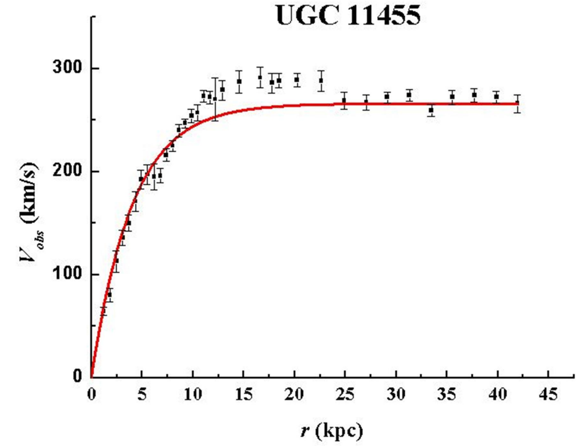

FIG. 18. Fitting results for UGC 11455.

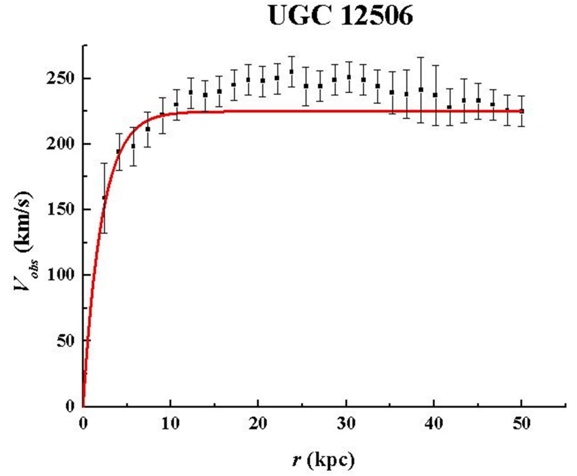

FIG. 19. Fitting results for UGC 12506.

Discussion and Conclusions

In this paper, we have tried to test the idea that the rotation curves of spiral galaxies could be resulting from the motion of their parts in a viscous medium, where a drag force perpendicular to the direction of motion is applied. No attempt in this work is made to show how such force is generated. The aim is only to test the assumption that once the stars are assumed to be moving under the effect of such a force, the rotation curves of the galaxies can be explained accordingly as a dynamic effect rather than being due to the existence of some sort of dark matter.

As for the viscosity function and since the viscosity of the medium is thought to be emerging through the interaction of baryonic matter with virtual states of the vacuum, it is quite reasonable to expect that the viscosity of the medium will not be constant all through, but will be some function of position. Accordingly, we have assumed certain position dependence that satisfies the very general boundary conditions in such a case. The fitting results we have obtained show that such an assumption is quite plausible.

Taking into consideration the approximations adopted by our model and the inevitable observational error bars shown in the figures, the results depicted in Figs. 2-19 show good agreement with observational data, at 95% confidence level. There, are some discrepancies in some cases; for example, the predicted rotation curve of galaxy NGC 2903 in Fig. 7 shows poor agreement with observations, where the velocity profile is peaking at the rim of the galactic bulge. This might be due to the internal structural circumstances inside this galaxy, as it is known that the central region of this galaxy has a very high rate of star formation [28], a factor indicating the existence of a strong gravitational potential within the galactic bulge. The high slope of velocity profile within the bulge is also in support of this explanation. A similar discrepancy is noticed in Fig. 15 for UGC 3205 depicting a cusp-core-like shape in the bulge region. Such a discrepancy was also obtained in MOND rotation curve for this galaxy [29]. Here, we agree with the explanation that this may be a result of streaming motions in the weak bar in this galaxy which cause the observed velocities to deviate significantly from the local circular velocity and lead to asymmetries in the observed H I velocity field. We also notice that our fitting of the rotation curve for UGC 03580 in Fig. 16 is poor. Our results are similar to those obtained for the MOND curve [29]. Generally, the morphology of the galaxies seems to play an important role in forming the velocity profile and such role can be accounted for within the detailed theory. It should be noted that in our simplified model proposed here, we have considered the ratio of the radius of the stars to their mass a/m to be unity. Obviously, this will be a crude approximation when it comes to consider the detailed morphology of the galaxies.

If the hypothesis proposed in this work is accepted, then an urgent need appears to develop a theory that should rigorously demonstrate how vacuum viscosity emerges out of the interaction of moving baryonic matter with the vacuum states. However, it should be noted that such a medium does not need to have its viscosity as an independent intrinsic property; rather, the proposed viscosity is an emergent dynamic property, which becomes available as masses move through the quantum vacuum. Evidently, here at this point, the theory is not yet established and some serious theoretical work is needed.

It is worth mentioning here that the drag force will cause the parts of the galaxy at the far rim to move with very low acceleration as these parts reach their terminal velocity. Here, our model meets with the MOND proposal [19], though the reasoning provided here is more profound and may have better physical explanation.

It would be worth mentioning that the emergent gravity proposal by Erik Verlinde [24] suggests the presence of an entropic force showing an elastic effect that causes higher gravity than expected on the basis of standard general relativity. This might be compared with the viscous force we are suggesting here, which causes a drag that effectively might be compared with the extra emergent gravity. However, recent investigations show that there are some reservations on the emergent gravity proposal in relation to that the radial acceleration relation does not explain rotation curves of spiral galaxies except on applying certain constrains on the mass-to-light ratio [25].

McGaugh, Lelli and Schombert [30] studied the radial acceleration traced by rotation curves and that predicted by the observed distribution of baryons in galaxies with different morphologies. They found a strong correlation clearly indicating that the dark matter contribution is fully specified by that of the baryons. Now, if we take the dark matter effect to be replaced by the emergent viscosity effect proposed in this work, we can fairly consider this finding as a supporting evidence for the case of emergent viscosity suggested here; such a viscosity is thought to be generated out of an interaction between quantum vacuum states and the baryonic matter.

If the notion of emergent viscosity is to be adopted, then the proposal of dark matter could be applied entirely on a cosmic scale too; the motion of the galaxies in space is hampered by the emergent viscosity. This makes the universe expand slower than expected. A slower expansion might indicate that the universe contains more matter; as such, the average density of the universe will appear higher than expected and consequently a dark matter assumption may be invoked. Therefore, if the drag force due to the emergent viscosity is adopted, then there is no need for dark matter. Certainly, some detailed calculations are needed once the theory for such an emergent viscosity is established to calculate the actual value of Hubble's parameter and compare it with observations. This will be another test of the theory besides what has been suggested for the rotation curves of the galaxies.

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