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► **To cite this version:**

Anton A. Lipovka. Gas kinetics in galactic disk. Why we do not need a dark matter to explain rotation curves of spirals?. 2018. hal-01832309v2

**HAL Id: hal-01832309**

**<https://hal.science/hal-01832309v2>**

Preprint submitted on 31 May 2019 (v2), last revised 24 Jul 2020 (v3)

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# Gas kinetics in galactic disk. Why we do not need a dark matter to explain rotation curves of spirals?

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May 29, 2019

## Abstract

In present paper, we analyze how the physical properties of gas affect the Rotation Curve (RC) of a spiral galaxy. We confirm that the gas kinetics must be taken into account to build an adequate model of a spiral galaxy. It is stressed, that while the inner part of the RC is subject of the Kepler law, for the correct description of the outer part of the RC, the collisional property of the gas should also be taken into account.

To confirm this fact we suggest both quantitative estimations and exact calculation to show how the outer part of the RC is related with the gas density of the galactic disk. We argue that the hydrodynamic approach is not applicable for the correct modeling of large-scale gas kinematics of the galactic disk and more general diffusion equations should be used. Proposed calculations are based on solving both the Kepler's and the Fick equations and was carried out for two edge-on galaxies NGC7331 and NGC3198, for which the precise measurements of the gas column densities and RCs are available. An excellent coincidence between the measured column density of gas and that calculated from observed RCs is obtained.

From our result it follows, that if the gas density is high enough (more than  $10^{-5}$  cm $^{-3}$ ), the RC for the outer part of the disc is formed by "wind tails" of gas.

On the basis of the obtained result, we calculate the total masses of the NGC7331 and NGC3198. They consist  $37.6 \times 10^{10} M_{\text{sun}}$  and  $7.7 \times 10^{10} M_{\text{sun}}$  respectively. Consequences for cosmology are discussed.

Keywords: Dark Matter; Rotation Curves; Gravitational Potential; Mass of spiral galaxy; gas kinetics.

Pacs numbers: 04.60.-m, 04.65.+e, 11.15.-q, 11.30.Ly

# 1 Introduction

Difficulties in explaining the kinematics of celestial objects within the framework of Kepler's law were first noted by James Jeans and Jacobus Kapteyn in 1922 and then confirmed by Jaan Oort in 1932 and by Fritz Zwicky in 1933. To solve the problem, it was assumed that there is some unobservable, invisible mass affecting the kinematics of the observed objects. It should be noted that these observations were carried out in optics (stars) and therefore dark matter was the only way out of this situation. Later, when radio astronomy developed, it became possible to observe galactic disks in the radio range (gas) as well. It turned out that large-scale gas motions may also not obey the Kepler's law. It was quite logical to assume that we are dealing with all the same dark matter in this case. For more than 80 years, the DM nature has been widely discussed by both astronomers and physicists, but no significant progress in understanding the nature of DM was achieved.

As is known, the need for the DM concept was mainly due to two problems: 1) Observed non-Keplerian Rotation Curves (RC)s of spiral galaxies and 2) The presence of additional invisible mass in clusters of galaxies, leading to the observed gravitational bounding of clusters and also to anomalously large gravitational lensing produced by the clusters. However, recently a significant progress has been achieved in finding of the missing mass in clusters, reported by Kovács et al. (2018). Authors argue that the missing baryons reside in large-scale filaments in the form of warm-hot intergalactic medium. For this reason, it can be recognized that the second item (excessive masses of the clusters) loses its urgency, whereas the RCs of spiral galaxies remains the most intriguing manifestation of the DM.

It should be noted, that there is also another approach to the explanation of the RC based on the Modified Newtonian Dynamics (MOND). However, this year Paolo, Salucci, and Fontaine (2019) have convincingly shown that MOND cannot explain the relationship of accelerations (the  $g$  vs  $g_b$  relation) and therefore it must be discarded. On the basis of the obtained results, the authors conclude that DM has no alternative to explain RC. But the situation with DM is even more intriguing, since recently more accurate observational data was published, that sheds light on the dark matter properties. Namely, it was shown that there is a significant correlation between the features of the galactic RC and corresponding spiral structure of the baryonic component: "The dark and baryonic mass are strongly coupled" (Mc Gaugh, Lelli & Schombert 2017; see also Sancisi 2004; McGaugh 2004; Möller & Noordermeer 2006). It is difficult (if at all possible) to realize this coupling within the framework of the conventional DM paradigm in which the DM is coupled with baryonic component by gravitation only, and the distribution of the DM is described by spherically symmetric functions obtained from numerical simulations discussed for example by Navarro, Frenk & White (1996); Merritt, et al. (2006); Katz, et al. (2017); Di Cintio, et al. (2014a) and Di Cintio et al. (2014b).

Moreover, on the one hand, as it was shown by Kroupa, Pawlowski and Milgrom (2012), cosmological models based on warm or cold DM are not able

to explain observed regularities in the properties of dwarf galaxies. On the other hand, last year the rotation curves for high redshifted galaxies were reported and it was clearly shown that a large fraction of massive high - redshifted galaxies are actually strongly baryon-dominated (see Genzel et al. 2017, Lang et al. 2017, and references therein). These data contradict the generally accepted scenario of galaxies formation on the DM halos.

The search for DM in laboratories is also unsuccessful despite the unprecedented efforts of many international collaborations. The FERMI experiment designed to search for annihilation of DM and anti-DM clearly shows negative result announced by Albert, et al. (2017). As part of the XENON collaboration, the radioactive decay of xenon-124 due to double-electron capture, which has a half-life of  $1.8 \times 10^{22}$  years, was detected (this indicates the highest sensitivity of the method) but no signs of dark matter were found (Aprile E. et al. 2019). SENSEI collaboration reports of world-leading constraints on dark matter – electron scattering for masses between 500 keV and 5 MeV (see Abramoff et al. 2019).

To make the picture more complete, two more facts should be added to the above. The first is that the stars of the halo (the old population of a spiral galaxy) move more slowly than the young population of the disk does. This fact required a special consideration of the component if we do suppose that the RCs, are formed by the spherically distributed DM.

The second one is the fact that as the distance from center increases, the stars velocity dispersion increases too and reach considerable values approximately at medium distance (for our Galaxy, for example, this distance starts from 10 kpc.). To explain this fact, we need to invoke some additional mechanisms because it scarcely can be obtained within the framework of an ideal, spherically distributed DM.

Summarizing, the unsatisfactory nature of the current explanation of the rotation curves of spiral galaxies becomes obvious. All mentioned above clearly indicate a serious problem with naive simulation of the spiral galaxy dynamics and mass distribution based only on the assumption of the dominant role of gravitational interaction. Moreover, it suggests the need for revision of actually used models and argues that more accurate modeling of the galactic baryon component and adequate consideration of all reasonable physical effects are strongly required. At present, such simulations of the density distribution are performed on the basis of the assumption of overwhelming gravitational force domination (see papers mentioned before). In this case, based on hydrodynamic simulations, it is concluded that the effect of gas kinetics on the formation of rotation curves is negligible, i.e. the gas properties are not taken into account when the pseudo - stationary structure of the gas disk is calculated (recall that the rotation curves for the most important - the outer part of the disk are observed mainly in the molecular lines and 21 cm line of neutral hydrogen, and therefore the influence of collisions of the hydrogen atoms and ions on the formation of the stationary gas fluxes, should at least be correctly assessed).

At the first glance, the hydrodynamic approach mentioned above, could become a standard calculation method in this case. But it hardly can be applied

because of two reasons.

1) We are not interested in local small scale movements, on the contrary, we need to calculate global RC of external part of a galactic disk.

2) Hydrodynamic approach can not be applied because of the extremely low density of gas resulting in significant free path lengths, that leads to violation of the conditions of the hydrodynamic applicability  $L_k \gg l_{fp}$ . For example the typical density for outer parts of disc is  $10^{-3} - 10^{-4} \text{ cm}^{-3}$  leads to  $l_{fp} = 3 - 30 \text{ pc}$ .

For this reason, the hydrodynamic approach becomes inappropriate, since the characteristic lengths  $L_k$  on which the values (density, temperature, pressure etc.) are changed considerably and become comparable or even less than  $l_{fp}$ .

The only reliable and not cumbersome method can be obtained directly from the kinetic equations the same way as it was made for hydrodynamic equations. In our paper we are going this way.

Namely, the kinetic equations should be first averaged over the volume in order to avoid the limitations imposed on the applicability of hydrodynamic equations, and only after such a procedure they can be integrated over the momentum. Doing so we obtain diffusion equation and evaluate the gas kinetic contribution to the RC formation. We prove that to model a disk of a spiral galaxy, the gas kinetics should be taken into account, because if the influence of the gas kinetics on the RC formation is neglected, it will leads to a completely incorrect (pure Keplerian) model of the galactic disk and, as a consequence, to wrong estimation of the gravitating masses and their distribution. We show that the solution of the Fick equations strongly implies that the rotation curve of the gas does depend on the gas density. For this reason if observed, this dependence can be used as a signature that directly proves the main role of the gas kinetics in formation of the outer part of RC. With the example of two edge-on galaxies NGC7331 and NGC3198, we argue that the observed gas distributions do correspond to the rotation curves and they are related through the Fick equations as it should be. Therefore, we show that it is the kinetics of the gas, that dominates in the formation of the rotation curves of spiral galaxies at large distances. We choose these two edge - on galaxies to minimize the influence of the 3D structure of galaxy on the column density, since we are interested in the disk component only.

So, one can conclude that the deviations of the spiral galaxies RCs from those determined by the Kepler's law, can easily be explained if we take into account the gas kinetics by using correct method. In fact the RCs at large distances are just the wind tails of the baryon gas that follows the preceding baryon matter in the case if the gas obeys the usual physical laws. For this reason we do not need the DM concept to explain rotation curves of spiral galaxies.

It should be noted here that wind in galaxies is not a new concept. For example a starburst-driven galactic wind in starburst galaxies is a well-known phenomenon that is widely discussed in the literature, see for example Jones et al. (2019), Sharp & Bland-Hawthorn (2010), Rekola et al. (2005) and references therein. However, in the case of large-scale movements and extremely low gas densities in outer part of disk that we are interested in, the standard hydrodynamic approach cannot be applied because of the limitations mentioned

above.

The article is organized as follows:

In the second section a preliminary estimates are made for main parameters of gas in the disk of a spiral galaxy. From the evaluations obtained here one can see that the gas kinetics plays a dominant role in the formation of the wind tails in the media out of equilibrium. But if so, the dependence of the outer part of RC on the gas density should be clearly manifested. The most interesting and convenient case for integration, corresponds to the constant RC for outer part of the disk. For this reason in the third part we obtain differential equations that describe the gas dynamics and then we calculate analytically the gas density as a function of distance for the outer disk of spiral galaxy in the case of constant RC, by using diffusion equations. It is known, that in observations the column density is measured, whereas the gas density depends on model. For this reason in the part 4 we calculate the column density to compare it with the observed one. As an example we consider two edge-on S-type galaxies with measured RCs and optical depth in 21 cm., as function of distance  $R$  from the center of galaxy. We show that the results obtained with the Fick equations, are in excellent agreement with the observational data. In conclusion the main results of the paper are summarized and important consequences are discussed.

## 2 Preliminary estimates.

As it was mentioned above, there are two very different components of galaxy population: stars and gas, which are used to measure the RC of galaxy in optics and in radio respectively. The first component is driven only by gravitation potential, whereas to describe the second one we should take into account collisions and the gas kinetics must be involved into consideration. To confirm this fact, let's evaluate some parameters of the gas. A rough estimate of the mean free path time for a hydrogen atom  $t_{fp} = (N\sigma V_t)^{-1}$  (here  $N$  is the density of the gas in  $sm^{-3}$ ,  $\sigma$  is cross-section for elastic collision and  $V_t$  is the mean thermal velocity of the atom) gives  $t_{fp} \approx 1.3 \cdot 10^{10}/N$  (sec) =  $4.1 \cdot 10^2/N$  (yrs). For the typical HI density outside of the  $R_{25}$ :  $N \approx 10^{-3} - 10^{-4}$  we obtain  $t_{fp} \approx 4.1 \cdot (10^5 - 10^6)$  yrs.

However, as we know, the intergalactic gas, as well as the hot gas component of the disk of a spiral galaxies is ionized. For this reason, we should estimate the mean free path of the proton. The free path length (see Lang 1974) is:

$$l_{fp}^* = \frac{m^2 V_{rms}^4}{z_1^2 z_2^2 N_e e^4 \ln \Lambda} \approx \frac{3.2 \cdot 10^6 T^2}{z_1^2 z_2^2 N_e e^4 \ln \Lambda}, \quad (1)$$

where

$$\Lambda = 1.3 \cdot 10^4 \sqrt{\frac{T^3}{N_e}} \approx 2 \cdot 10^{11}, \quad (2)$$

so  $\ln \Lambda = 26$ , and the proton's mean free path is  $l_{fp}^* = 10^{16} \text{cm}$  for the temperature  $T = 3000 \text{K}$ . In this case the mean free path time can be evaluated as  $t_{fp}^* = l_{fp}^*/V_t = 10^{10} \text{sec} = 3 \cdot 10^2 \text{yrs}$ . As one can see these time ( $t_{fp}$  or  $t_{fp}^*$ ) are much smaller than the characteristic time of life of the galaxy, so collisions must be taken into account.

Thus, one can see that for description of the gas located in the outer  $R > R_{25} \gtrsim R_0$  part of galactic disk, the complete gas dynamics equations should be used to explain the observed RCs. Here  $R_0$  denotes a distance to the transition zone at which the contribution of the gas kinetics in formation of wind tails (and hence RCs) begins to dominate, if compared with that caused by Kepler's law.

Now let's make another estimation to answer the question: "Will the gas be able to follow the underlying falling baryon matter to form the wind tails?". From observations we know that baryon matter of a S-type galaxy moves along a spiral (note that a galaxy is not a stationary object. it has its beginning, it has the end, and it evolves over time, consuming intergalactic gas).

In this case we can imagine the underlying baryonic matter as a piston (baryon matter in inner  $R < R_0$  part of galaxy's disk) that moves in the spiral tunnel with ideal walls (we can apply the homogeneous boundary conditions in this particular case), and which is followed by the HI gas (here we will not consider the processes of star formation, that dilute the gas component, but we only note here that accounting for such processes will increase the effects under discussion). The mean acceleration of the "piston" for typical galaxy can be roughly evaluated as  $\langle w \rangle = \Delta V / \Delta t = (200 \text{Km/s}) / (10^9 \text{yrs}) = 10^{-9} \text{(cm/s}^2\text{)}$ . By taking into account the evaluation of  $t_{fp}$  (or  $t_{fp}^*$ ) made before, we can estimate the variation of the piston's velocity  $\Delta V$  during the mean free path time of the hydrogen atom. Even in the worst case of  $t_{fp}$  for neutral component, we have  $\Delta V = \langle w \rangle t_{fp} = 10^{-9} \cdot 2 \cdot 10^{10} / N = 20/N \text{(cm/s)}$ . For typical density  $N = 10^{-3} \text{(cm}^{-3}\text{)}$  we obtain  $\Delta V = 2 \cdot 10^4 \text{(cm/s)} \ll V_t \approx 10^6 \text{(cm/s)}$ . So one can conclude that even the neutral gas will follow the "piston" if the gas density is high enough:  $N \text{(cm}^{-3}\text{)} \geq 2 \cdot 10^{-5} \cdot (10^6 / V_t)$ . We stress here that it is an important result which can qualitatively explain the great variety of the RCs shapes because of their dependence on the gas density. From this estimate it can be seen that when the density is small ( $N \text{(cm}^{-3}\text{)} < 2 \cdot 10^{-5} \cdot (10^6 / V_t)$ ), the wind tails will not be formed and the corresponding RC will decrease to coincide with Keplerian one.

These were rather crude assessments, suggested here to show simplistically the physics of processes under discussion. To conclude this part we would like to stress that even in consequence with these simple estimations, one can see that the gas, driven by collisions, will follow easily the underlying baryon matter. Actually the gas under consideration forms the wind tail which rigidly follows the underlying baryon matter which, in turn, is driven mainly by the gravity at distances  $R < R_0$ . This way the absence of RC of S-type galaxies in the early universe, reported by Genzel et al. (2017), can be explained easily. Namely, rough estimate of distance over which the wind tail (or, the same RC) will spread is  $t \cdot V_t \approx 10^{10} \text{yrs} \cdot 3 \cdot 10^7 \cdot 10^6 \approx 3 \cdot 10^{23} \text{(cm)} = 100 \text{kpc}$ . This trivial evaluation clearly shows why the RC measured with HI line are seen in our

epoch, but can not be observed in early universe, where  $t < 10^{10}$  yrs., as it was recently observed and reported by Genzel et al. (2017).

### 3 Gas density as a function of distance for constant RC

At present, it is assumed that taking into account collisions in a gas has a negligible effect even for small galaxies (see, for example, Dalcanton & Stilp 2010) and for large spirals it simply does not matter. Such conclusions are based on hydrodynamic simulation and the assumption that the Euler equation, and hence the Bernoulli equation, is always satisfied. However, this is not the case with a highly turbulent rarefied gas, and therefore it is impossible to trust numerous calculations based on such a naive model. Unfortunately, this error is very common in hydrodynamic calculations applied to galactic disks, the number of published works is huge and therefore we will mention here only a couple of articles as an illustration of the problem under discussion: Shevchenko, Vasiliev and Shchekinov (2017); Joung et al. (2009). The pictures presented by the authors clearly show that the characteristic scale of inhomogeneities, on which the gas parameters changes significantly, is  $L_k = 1 - 10$  pc, while the mean free path of a particle at a density of  $10^{-3}$  is  $l_{fp} = 3 - 30$  pc. Let us consider the calculation method in more detail.

It is well known that the hydrodynamic equations can be obtained from kinetic equations by integrating them. Kinetic equation for one type of particles is:

$$\frac{df}{dt} + \frac{d}{dx^\alpha}(v^\alpha f) = Stf. \quad (3)$$

Integrating over momentum  $p$  under assumption that variations of all parameters ( density, velocity, temperature, etc.) are small at the mean free path length  $l_{fp}$ , i.e. characteristic length  $L_k \gg l_{fp}$ , we obtain the continuity equation.

$$\frac{dn}{dt} + \frac{d}{dx^\alpha}(v^\alpha n) = 0. \quad (4)$$

Other hydrodynamic equations can be obtained by the same way, by multiplying the kinetic equation by  $p$  and energy  $\varepsilon$  and then integrating, but they will not give us something new and lead to the same restriction for hydrodynamic equations be applicable:

$$L_k \gg l_{fp}, \quad (5)$$

which imposes some restrictions on the hydrodynamic equations applicability. Unfortunately many authors who investigate numerically the kinematics of ISM, violate these restrictions (see for example papers cited above). Thus, the results obtained by them are hardly credible.



To eliminate this restriction, we start with the same kinetic equation (3) as it takes place in the case of hydrodynamics. To obtain eq.(4) we considered condition (5) to hold. But if this is not the case, i.e.  $(v^\alpha f)$  is changed significantly within the scale  $l_{fp}$ , then the only thing we can do - is average over a volume (recall that we are not interested in small-scale gas motions and therefore we can average).

Now we rewrite (3) as

$$\int \int \left( \frac{df}{dt} + \frac{d}{dx^\alpha} (v^\alpha f) \right) d^3x d^3p = 0, \quad (6)$$

and integrate it. First term gives  $dm/dt$  where  $m$  is a mass inside the volume of integration.

The second term can be transformed to  $\Delta S dn/dx^\alpha$ , so finally we have

$$\frac{dm}{dt} = -D \Delta S \frac{dn}{dx^\alpha}, \quad (7)$$

where  $D = \langle v \rangle \Delta l$ .

This is well-known diffusion equation.

Summarizing, we note that the hydrodynamic equations can not be applied to simulate the large scale structure of ISM of low density. Moreover, we do not need this approach to calculate RC. By integrating over a volume and making the problem insensitive to small-scale turbulences, we obtain the diffusion equation (7) suitable to describe the large-scale movements of the rarefied gas in outer part of the disk.

From observations and numerical cosmological simulations, we know the well established fact, that galaxies evolve over time. Therefore this is the more or less homogeneous gas of the pre-galactic epoch, from which the young galaxies begin to form. Gradually they pick up the gas from the surrounding intergalactic media and finally, at the present epoch, we can observe a large variety of massive galaxies with developed spiral structures. This actually mean that the gas in outer parts of spiral galaxy follows a spiral (please do not confuse it with the galactic arms, or spiral structure) which we can write as

$$R = R_0 e^{k(\varphi)}, \quad (8)$$

where the distance  $R_0$  was defined before. In this case for the total longitudinal  $V_{||}$  and tangential  $V_{\perp}$  velocity one can write  $V_{||} = k' V_{\perp}$ , where  $k'$  is  $\partial k / \partial \varphi$ . But the longitudinal velocity is given by the Fick's first law of diffusion obtained before (7):

$$V_{||} = -\frac{D}{N} \frac{\partial N}{\partial R}, \quad (9)$$

or

$$k' V_{\perp} = -\frac{D}{N} \frac{\partial N}{\partial R}, \quad (10)$$

where  $D$  is the diffusion coefficient,  $N$  is density and  $R$  is distance in the cylindrical coordinate system. Formally speaking one can put into equation (8) the HI gas density, measured for different S-type galaxies and obtain corresponding RCs for outer part of disk, but it is methodologically more correct and easier to solve the inverse problem. Namely, we are interested in the question: "which HI column density function corresponds to the case of the constant rotation curve of baryon matter in absence of DM for an S-type galaxy?" Consider this problem in more detail.

By taking into account the fact that  $D = const$  for very depleted gas and assuming that  $V_{\perp} = V_{K0} = const.$  (here  $V_{K0}$  is Keplerian velocity at the distance  $R_0$ ) we obtain

$$\frac{D}{n} \frac{1}{R_0} \frac{\partial n}{\partial r} = k' V_{K0}, \quad (11)$$

where we introduce  $n = N/N_0$ ,  $r = R/R_0$ , and by definition

$$V_{K0} = \sqrt{\frac{MG}{R_0}}. \quad (12)$$

Integrating (11) we obtain:

$$n = n_0 \exp \left\{ -\frac{V_{K0} R_0 k'}{D} r \right\}, \quad (13)$$

where

$$n_0 = \exp \left\{ \frac{V_{K0} R_0 k'}{D} \right\}. \quad (14)$$

As one can see this density distribution depends exponentially on the distance  $r$ . Unfortunately we are not able to realize a direct measurement of the gas density of the galactic disk. The only we have are the observed column densities measured in 21 cm., so now we are going to calculate the column density formed by distribution (13).

## 4 Column density

By definition the column density is

$$N_L = 2 \int_0^L N dl, \quad (15)$$

where  $N$  is density function. By taking into account that  $l^2 = R^2 - \rho^2$ , the eq. (15) can be rewritten as:

$$N_L = 2N_0 R_0 \int_{r=\rho/R_0}^{r_{\max}} \frac{nrdr}{\sqrt{r^2 - \frac{\rho^2}{R_0^2}}}. \quad (16)$$

Expanding the expression in a row:

$$\frac{1}{\sqrt{1 - \left(\frac{\rho}{rR_0}\right)^2}} \approx 1 + \frac{1}{2} \left(\frac{\rho}{rR_0}\right)^2 + \frac{3}{8} \left(\frac{\rho}{rR_0}\right)^4, \quad (17)$$

we obtain

$$N_L(\rho) \approx 2N_0R_0 \int_{r=\rho/R_0}^{r_{\max}} n(r) \left[ 1 + \frac{1}{2} \left(\frac{\rho}{rR_0}\right)^2 + \frac{3}{8} \left(\frac{\rho}{rR_0}\right)^4 + \dots \right] dr, \quad (18)$$

where  $n(r)$  is given by relation (13). So, the column density can be expressed as

$$N_L \approx N_{L1} + N_{L2} + N_{L3}, \quad (19)$$

here

$$N_{L1} = 2N_0R_0 \int_{r=\rho/R_0}^{r_{\max}} e^{-\varkappa(r-1)} dr, \quad (20)$$

$$N_{L2} = N_0R_0 \left(\frac{\rho}{R_0}\right)^2 \int_{r=\rho/R_0}^{r_{\max}} e^{-\varkappa(r-1)} \frac{dr}{r^2}, \quad (21)$$

$$N_{L3} = \frac{3}{4}N_0R_0 \left(\frac{\rho}{R_0}\right)^4 \int_{r=\rho/R_0}^{r_{\max}} e^{-\varkappa(r-1)} \frac{dr}{r^4}, \quad (22)$$

and

$$\varkappa = \frac{V_{K0}R_0k'}{D}. \quad (23)$$

These expressions can be integrated and we obtain for the first term:

$$N_{L1}\left(\frac{\rho}{R_0}\right) = \frac{2N_0R_0}{\varkappa} e^{-\varkappa\left(\frac{\rho}{R_0}-1\right)} \left(1 - e^{-\varkappa\frac{\rho}{R_0}\frac{\Delta V}{V}}\right), \quad (24)$$

where  $\Delta V/V$  is the observed relative bandwidth by velocity.

Estimating the integrals (21) and (22), it is easy to show that the second, third and higher terms of our expansion will have the same exponential behavior ( $\propto \exp(-\varkappa(\rho/R_0 - 1))$ ), but in absolute value they will be much smaller than the first term (24). For this reason for our aim we can take expression (24) as a good approximation for the column density. The column density (20,24) is compared with observed values suggested by Begeman (1987, 1989) and Bigiel et al. (2010) for NGC7331 (fig.1) and NGC3198 (fig.2).

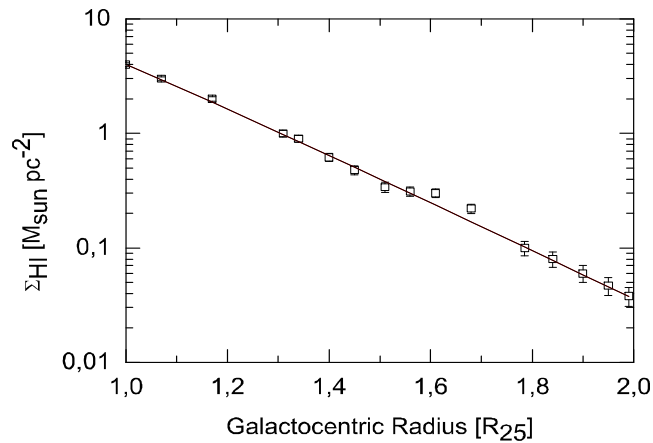


Figure 1: Measured (squares) suggested by Begeman (1987); Bigiel et al. (2010) and calculated with (24) (solid line) HI column density for NGC7331.

These two galaxies were chosen because they are seen edge on by observer. Due to this circumstance, in this case, there is no need to take into account the angle of inclination of galaxy, that simplifies the modeling.

As one can see from the fig.1 and fig.2, the calculated (in assumption  $RC=const$ ) column density distributions excellently coincide with the observed ones for very different galaxies, characterized by different mass and slopes of the column density function. So we can conclude that RC at large distances  $R > R_0$  are formed mainly by wind tails of gas that obeys not only the Kepler's law, but also the diffusion equations. For this reason we do not need dark matter to explain the rotation curves of spiral galaxies.

Now (by taking into account that RC consists of two parts: 1)  $R < R_0$  where the gravitation dominates, and 2)  $R > R_0$ , where contribution of gas kinetics becomes dominant) we estimate the masses of two galaxies mentioned above using their measured RC suggested by Begeman (1987), Begeman (1989) and de Blok et al. (2008), by using previously obtained model for the baryon

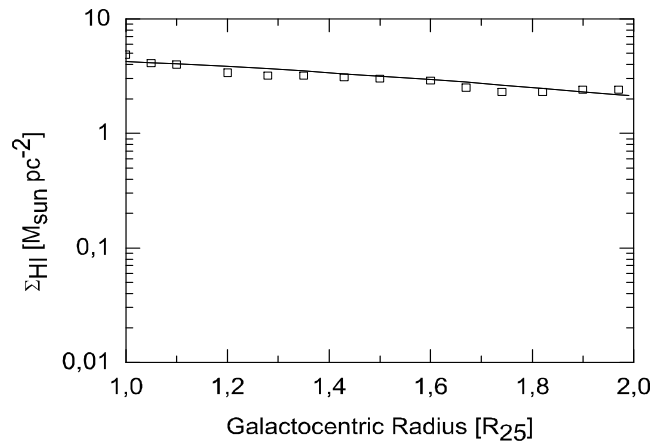


Figure 2: Measured (squares) suggested by Begeman (1987); Bigiel et al. (2010) and calculated with (24) (solid line) HI column density for NGC3198.

mass distribution (see Lipovka 2018). The coefficients  $\alpha_k^*$  and  $\beta_k^*$  we immediately find from approximation of the RCs for these two galaxies. Figures 3 and 4 demonstrate results of such approximation for NGC7331 and NGC3198 respectively.

The thick straight line (the constant part of the RC) at the figures 3 and 4 corresponds to the wind tails (rotation curves) formed by gas which obeys the diffusion equations and has column densities shown at figures 1 and 2. As it can be seen, the wind tails (constant RCs) extend exactly to the distance where the column density function has the exponential form (24).

Obtained coefficients for NGC7331 are  $\alpha_1^* = 0.39$ ,  $\beta_1^* = 0.112$ ,  $\alpha_2^* = 5.5$ ,  $\beta_2^* = 28.8$ , and for NGC3198 we find  $\alpha_1^* = 0.21$ ,  $\beta_1^* = 0.33$ ,  $\alpha_2^* = 0.55$ ,  $\beta_2^* = 6.0$ . Now the masses of these galaxies can be obtained immediately with

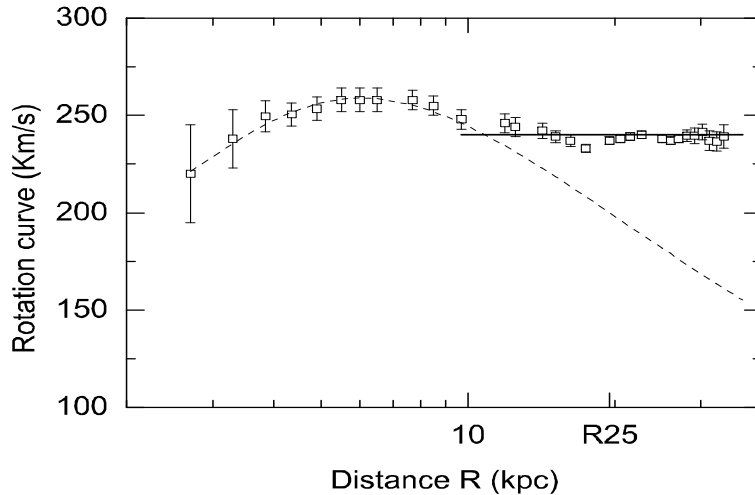


Figure 3: Measured (squares) as suggested by Begeman (1987, 1989), de Blok et al. (2008), and calculated with the model of Lipovka (2018) (dashed line) rotation curve for NGC7331. Wind tail (external part of RC) that corresponds to the HI distribution (see fig.1) is shown by the horizontal bold solid line.

relation for the total baryon mass suggested by Lipovka (2018). In this case for NGC7331 we find  $M_{7331} = 37.6 \cdot 10^{10} M_{\odot}$  and for NGC3198 the total mass is  $M_{3198} = 7.7 \cdot 10^{10} M_{\odot}$ .

## 5 Conclusions and discussion

In present paper we show that the commonly accepted explanation of the rotation curves of spiral galaxies, based on the naive simulation of the spiral galaxy dynamics and mass distribution in approach of the dominant role of the gravitational interaction, is not complete and can not be considered as satisfactory.

We argue that the influence of the gas kinetics on the formation of rotation curves can not be neglected, i.e. the physical properties of the gas must be taken into account to determine the quasi - stationary structure of the gaseous disk (recall that the rotation curves for the most intrigue - the outer part of the disk, are observed in the molecular lines and 21 cm. line of neutral hydrogen), and therefore the influence of collisions of the hydrogen atoms and ions on the formation of the stationary gas fluxes must at least be correctly estimated. In our paper, we suggest such estimations. Moreover, we prove that for any disk model of a spiral galaxy, the gas kinetics should be taken into account, because

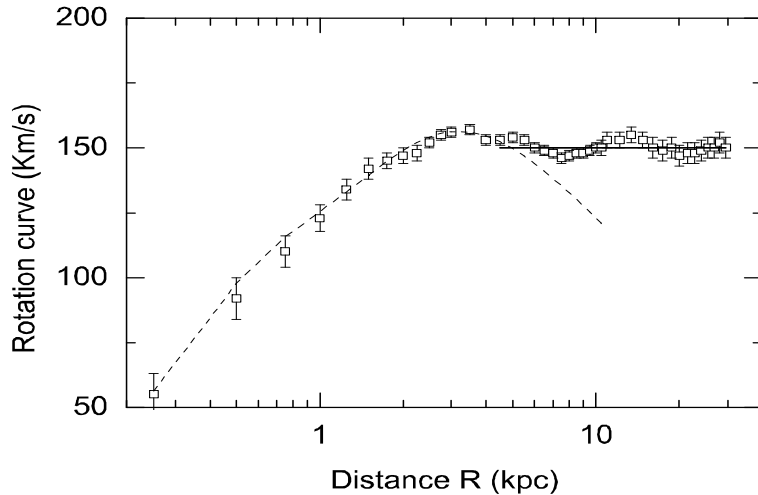


Figure 4: Measured (squares) as suggested by Begeman (1987, 1989), de Blok et al. (2008), and calculated with the model of Lipovka (2018) (dashed line) rotation curve for NGC3198. Wind tail (external part of RC) that corresponds to the HI distribution (see fig.2) is shown by the horizontal bold solid line.

if the influence of the gas kinetics on the RC measured in 21cm. is neglected, it leads to a completely incorrect model of the galactic disk and, as a consequence, to wrong estimation of the gravitating masses and their distribution. We show that the solution of the Fick equations implies that the rotation curve of the gas depends on the gas density. Such dependence, if observed, will prove the importance of the gas kinetics in formation of outer part of RC. We consider as an example two edge-on galaxies NGC7331 and NGC3198. The observed gas distributions do correspond to the rotation curves and they are related by the Fick equations. Therefore, we conclude that it is the kinetics of the gas that dominates in the formation of the rotation curves of spiral galaxies at large distances and no DM needs to explain RC.

A couple of words should be said on the rare stars formed in the outer part of the disk. It is known, the RC for outer part of disk is measured not only in 21 cm., or in molecular lines, but sometimes also in optics by using a spectra of rare and young stars that were formed in this region. In this case approximately the same (as the gas has) tangential velocities of remote rare stars that moves out of  $R_0$  can be explained as momenta obtained from the gas of which the stars were formed. For this reason, whereas the rotating gas is bounded, these remote stars that moves with the same velocities, are not gravitationally bounded and they will leave the host galaxy in future.

The main results of the paper can be summarized as follows:

1) We argue that to describe correctly the observed RCs profile of spiral galaxies, not only gravitation interaction, but also the physical properties of the gas should be taken into account by correct way.

2) We show that RCs consist of two parts. One (inner part) is formed by collisionless ideal "gas", consisting of stars, and in this case the gravitation interaction dominates, whereas another part (localized in the outer region of disk) is formed mainly by the real gas, whose motion obeys not only the gravity, but also the diffusion equations. For this reason the gas kinetics will contribute to the formation of the gas stationary fluxes (and, consequently, to formation of outer part of the observed RC) and in this case corresponding part of the RC must be calculated with consideration of the diffusion equations.

3) On the basis of the Fick equations, the direct and exact relationship between flat RC and the density function of the outer gas is obtained. From the measured rotation curves, we calculate the HI column density as function of distance R for two edge-on spiral galaxies: NGC7331 and NGC3198. The calculated column densities are in excellent agreement with the observed ones.

4) By taking into account the facts proved above, (that the RC consists of two parts that are governed by different physics) the total masses of two edge-on spiral galaxies are calculated. Our evaluation for the NGC7331 is  $M_{7331} = 37.6 \cdot 10^{10} M_{\odot}$  and for NGC3198 the total mass consists  $M_{3198} = 7.7 \cdot 10^{10} M_{\odot}$ .

Thus, we have shown that we do not need dark matter to explain rotational curves of galaxies. The need for DM arose from the use of an inadequate hydrodynamic model, which, due to initial constraints, cannot be applied to calculate the dynamics of a rarefied gas in the outer regions of galactic disks.

Some words should be said about cosmology. The DM is believed to play the key role in formation of the observable structure in the universe. As is known, in the absence of dark matter and in the framework of the (pseudo) Riemannian Universe, cosmological time is not enough to form the observed structure. In this case the only reasonable extension of the existing paradigm, which satisfies the principle of the Occam's razor, is the extension of the (pseudo) Riemannian geometry to the Finslerian one, that will give the necessary time for the formation of the observed structure. As it was said by Shiing-Shen Chern (1996), "Finsler geometry is just Riemannian geometry without the quadratic restriction". Actually the (pseudo-) Riemannian geometry is a very special case of the Finslerian one, and there is no reason for this particular quadratic restriction. Moreover, only within the framework of the Finslerian geometry, the cosmological constant appears in a natural way from geometry itself, it has natural explanation and it becomes possible to unify quantum theory and gravity (see Lipovka 2014, Lipovka 2017).

Besides that on the Finslerian manifold the Planck constant calculated from the first principles (with measured cosmological parameters) coincides with it's experimental value up to second digit (Lipovka 2017), whereas if we calculate it for the (pseudo-) Riemannian world, we find that the Planck constant differs by factor 3/2 from it's exact value (Lipovka, Cardenas 2016). These are more than serious arguments in favor of the Finsler geometry. If we also add to this



the observable absence of dark matter in the early Universe and in clusters of galaxies (see introduction), its absence in the disks of galaxies (this work), then the need to move to the Finsler world will become obvious.

## 6 Acknowledgments

I would like to express my deepest gratitude to Dr. I.V. Gosachinsky for useful discussions.

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