Spiral galaxies without nonbaryonic Dark Matter?

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We report on a number of galaxies whose rotation could be accounted for without non-baryonic dark matter. In the framework of axi-symmetric global thin disk model this is possible for galaxies NGC 7793, NGC 1365, NGC 6946, NGC 4736, UGC 6446 and for the Milky Way, NGC 891, NGC 2403, NGC 4559, NGC 4302, NGC 5775. For the latter 6 galaxies (including Milky Way) the measurements of the vertical gradient of rotation are available and can be compared with the values predicted in the disk model. Our preliminary results may suggest that the problem of missing mass in spiral galaxies is not so severe as expected so far.

1 Introduction

Customary approach to modeling of rotation curves assumes that spiral galaxies consist of three main baryonic subsystems: the central bulge, the disk and a halo of stars, satellite compact objects and gas, all three components immersed in a spheroidal non-baryonic dark halo. The dynamics is dominated by the non-baryonic component.¹ The luminous and nonluminous baryonic matter comprises only 20% of the total mass in galaxies which, for example, can be inferred from analyzing radial motions of luminous external compact halo objects like in the Milky Way galaxy² (when a non-baryonic halo model is assumed, although a recent result in a different approach suggests that Galaxy mass can be much lower³ [and references therein]). However, not all observational facts are consistent with this picture. In this paper we report recent results concerning our study of galaxies in the framework of a global thin disk model, assuming gross mass distribution to form a flattened structure resembling a disk rather than a spheroid. This approach leads to physically viable results. We obtain low mass-to-light ratios with column mass density overlapping with the measured amount of gas at the galactic outskirts. In this model we also obtain correct values for the vertical gradient of the azimuthal component of rotation.

2 Thin disk model

The source of the gravitational potential in the framework of global disk model is approximated by a substitute axi-symmetric column mass density forming a thin disk in the mid-plane. The rotation law on circular concentric orbits of the disk is identified with the observed galactic rotation curve. There is a unique relation between the rotation law \( v(r) \) and the surface mass distribution \( \sigma(r) \) and the inverse relation, given by the following mutually invertible integral.
transforms derived in $^4$ that can be simplified to $^5$

$$\sigma(r) = \frac{1}{2\pi^2 G} \int_0^\infty \left[ \frac{K(\kappa(x))}{1+x} - \frac{E(\kappa(x))}{1-x} \right] \frac{v^2(r, x)}{rx} \, dx, \quad \kappa(x) = \frac{2\sqrt{x}}{1+x}.$$  \hfill (1)

$$\frac{v^2(r)}{r} = 2G \int_0^\infty \left[ \frac{K(\kappa(x))}{1+x} + \frac{E(\kappa(x))}{1-x} \right] \sigma(r, x) \, dx,$$  \hfill (2)

where $E$ and $K$ are complete elliptic integrals defined in $^6$. In studying galaxies with the help of above formulae, it is assumed that a galaxy is a flattened disk-like object rather than spheroidal and that the motion of matter is predominantly circular.

It is important to stress that mass density $\sigma(r)$ cannot be uniquely determined from the measured part of rotation curve, since $\sigma(r)$ involves integration of the rotation law also beyond the range of radii covered by the measurements and regions where matter is present (note also, that the rotation at a given radius depends also on the mass distribution beyond that radius, which is a qualitative difference between spheroidal and flattened systems). One of the consequences is that the predicted mass density falls off rapidly close to the end point of rotation data due to cutting off the integration. This and other 'cutoff' effects were discussed and illustrated in detail in $^4$, where it was also given an argument showing that despite this non-uniqueness, the mass distribution can be determined from rotation with a satisfactory accuracy in an internal part of a region covered by the rotation data.

To bypass the cutoff effect or reduce it, some additional data complementary to the rotation data are indispensable. To this end a radio measurements of the gas amount (like hydrogen) can be used. These measurements provide the lower limit for the mass density at larger radii. All the data can be made self-consistent and provide a global mass distribution by means of iterations, so that the density of dynamical mass inferred from the rotation curve at lower radii with the help of integral (1) continuously overlaps with the mass density of gas at larger radii. In effect, the global mass density after substitution to (2) gives correct rotation curve. An example of such an iteration scheme we described in $^7$ for galaxy NGC 4736. Based on such obtained column mass density supplemented with the luminosity measurements, the local mass-to-light ratio can be inferred (not assumed) and it turns out to be a variable function of the distance in the disk, see Fig.1. A similar procedure can be repeated for various other spiral galaxies. The example results are summarized in Tab.1. It is seen that the mass-to-light ratio is low, indicating that the luminous mass suffices to account for the rotation data and that there is no need for invoking other forms of matter.

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Figure 1: Results for galaxy NGC 4736. a) Rotation curve: THINGS measurements [solid circles] $^{12}$, the model [solid line], and comparison with a high resolution rotation curve $^3$. b) the model global surface mass density [solid line], surface mass density of HI+He [open circles]; and the surface brightness: B-band [solid squares], V-band [solid triangles], I-band [solid circles] $^{14}$. c) mass-to-light ratio profile (HI+He excluded).
<table>
<thead>
<tr>
<th>name</th>
<th>NGC 7793</th>
<th>NGC 1385</th>
<th>NGC 6946</th>
<th>NGC 4736</th>
<th>UGC 6446</th>
</tr>
</thead>
<tbody>
<tr>
<td>distance [Mpc]</td>
<td>3.38 A</td>
<td>18.6 L</td>
<td>6.0 M</td>
<td>4.7 T</td>
<td>18.6 C</td>
</tr>
<tr>
<td>morph. type</td>
<td>SAd A</td>
<td>SBB B</td>
<td>SAbc B</td>
<td>Sbb B</td>
<td>Sa G</td>
</tr>
<tr>
<td>$L_B [10^{10} M_\odot]$</td>
<td>0.3 K</td>
<td>9.81 E</td>
<td>1.64 H</td>
<td>1.3 S</td>
<td>0.218 J</td>
</tr>
<tr>
<td>$M_{H2} [10^{10} M_\odot]$</td>
<td>0.12 A</td>
<td>2.36 E</td>
<td>0.97 M</td>
<td>0.067 T</td>
<td>0.434 G</td>
</tr>
<tr>
<td>M$^*$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: The results obtained in the framework of thin disk model for several galaxies using measurements data from: A$^{15}$, B$^{13}$, D$^{16}$, E$^{17}$, F$^{18}$, G$^{19}$, H$^{20}$, I$^{21}$, J$^{22}$, K$^{23}$, L$^{24}$, M$^{25}$, O$^{11}$, P$^{12}$, R$^{26}$, S$^{14}$, T$^{27}$

Figure 2: Galaxy NGC 4559. [Left]: disc rotation curve (solid circles) and the anomalous gas rotation curve above the disk (open circles), both from 28. The solid lines are rotation curves predicted by our model at various heights above the mid-plane at $z = 0.6, 1.2, 1.8, 2.4, 3.0$ and $3.6$ kpc. The dashed line is the rotation curve predicted at $z = 4$ kpc; [Right]: the azimuthal velocity as a function of the vertical distance from the mid-plane. The points represent the velocity values averaged over the interval $r \in \{2.5, 6\}$ kpc, the bars show the standard deviation in this interval.

3 The vertical gradient of rotation

Thanks to the constantly improving quality of measurements, it has become possible to determine the vertical structure of the rotation above the galactic disc. This enables to test models of mass distribution in spiral galaxies more accurately. In the thin disk model framework discussed above one can relate the column mass density to the vertical structure of the azimuthal component of rotation $v_\phi(r, z)$, assuming the approximation of quasi-circular orbits above the mid-plane $z = 0$. Then, as we showed in 10,

$$v_\phi^2(r, z) = \int_0^{\infty} \frac{2G\sigma(\chi)}{\sqrt{(r+\chi)^2 + z^2}} \left[ K(k) - \frac{\chi^2 - r^2 + z^2}{(r + \chi)^2 + z^2} E(k) \right],$$

where $\sigma(r)$ is assumed to have been determined by iterations. The results for the predicted behaviour of the vertical gradient $\partial_z v_\phi(r, z)$ is shown in Fig.2 and Tab.2. The simple model gives high gradient values consistently with the measurements.

4 Summary

The results shortly reported in this work for a sample of galaxies (Milky Way, NGC 891, 1385, 2403, 4302, 4559, 4736, 5775, 6946, 7793 and UGC 6446) suggest in the framework of Newtonian gravitation that one can describe spiral galaxies consistently with the measurements and without invoking large amounts of unseen (non-baryonic) dark matter. For several galaxies it was also
Table 2: The vertical gradient of rotation in the framework of thin disk model for several galaxies

<table>
<thead>
<tr>
<th>Name</th>
<th>Milky Way</th>
<th>NGC 891</th>
<th>NGC 2403</th>
<th>NGC 4559</th>
<th>NGC 4302</th>
<th>NGC 5775</th>
</tr>
</thead>
<tbody>
<tr>
<td>distance [Mpc]</td>
<td>14.5</td>
<td>9.5</td>
<td>3.24</td>
<td>9.7</td>
<td>16.8</td>
<td>24.8</td>
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<tr>
<td>mass [10^{10}M_\odot]</td>
<td>5.52</td>
<td>4.82</td>
<td>4.82</td>
<td>5.05</td>
<td>5.05</td>
<td>9.65</td>
</tr>
<tr>
<td>( \Delta v_\phi ) observed \ [\text{km/s/kpc}]</td>
<td>-22.46</td>
<td>-17.5 \pm 5.9</td>
<td>-12</td>
<td>-10</td>
<td>-31 \pm 19.8</td>
<td>-8 \pm 4</td>
</tr>
<tr>
<td>z- segment [kpc]</td>
<td>(0.02, 0.1)</td>
<td>(1.2, 4.8)</td>
<td>(0.4, 2.4)</td>
<td>(0.2, 4)</td>
<td>(0.4, 2.4)</td>
<td>(1.2, 3.6)</td>
</tr>
<tr>
<td>r- segment [kpc]</td>
<td>(3, 8)</td>
<td>(4.02, 7.03)</td>
<td>(4.02, 7.03)</td>
<td>(3.1, 19.7)</td>
<td>(2.5, 6)</td>
<td>(0, 12)</td>
</tr>
<tr>
<td>( \Delta v_\phi ) predicted \ [\text{km/s/kpc}]</td>
<td>-21.3 \pm 4.2</td>
<td>-19.9 \pm 4.3</td>
<td>-10 \pm 4</td>
<td>-7.2 \pm 2.4</td>
<td>-22.7 \pm 8.4</td>
<td>-12 \pm 4.3</td>
</tr>
</tbody>
</table>

possible to compare with a good result the predictions of the disk model with the measured large values of the vertical gradient of rotation.

Acknowledgments

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References

6. Ryzhik, I. M., Gradstein, I. S. Tables of Integrals, sums, series and products, Moscow, Leningrad, 1951