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# Comparison of fits of mass density profiles for dark matter haloes

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**Abstract.** In this work, we present a brief comparison between the dark matter profile fits for three galaxies, UGC 05721, NGC 3198 and the Milky Way. We observe that the Burkert profile fits very well for the selected galaxies, in the case of the Milky Way, both Burkert and NFW presented good fits.

**Resumo.** Neste trabalho, apresentamos uma breve comparação entre o ajuste dos perfil de matéria escura para 3 galaxias, UGC 05721, NGC 3198 e a Via Lactea. Observamos que o perfil Burkert se ajusta muito bem para as galaxias selecionadas, no caso da Via Lactea, tanto o Burkert quanto o NFW apresentaram bons ajustes.

**Keywords.** Galaxy: kinematics and dynamics – Galaxy: structure – Galaxy: halo

## 1. Introduction

The presence of dark matter in galaxies is one of the models that explains the high velocities observed in rotation curves. Since the circular velocity must be expressed as a function of $M(R)$, and this, in turn, must depend on $\rho(R)$, which is the mass density, a model that can rigorously express what is observed must be defined. Thus, several models for the mass density emerge. In this work, we will analyze which model best fits the observational data, studying the Burkert, NFW, Isothermal and Einasto profiles, and their fits to the rotation curves of the galaxies UGC05721 and NGC3198, taken from the SPARC catalog Lelli et al. (2016), and of the Milky Way extracted from Sofue (2020).

## 2. Methodology

The data presented in the SPARC catalog provide the velocity contribution from the Atomic Gas and the Disk. However, the mass-to-luminosity ratio ($\gamma_D$) of the disk is parameterized to 1, so it is first necessary to find the best fit for such a ratio to what is known for spiral galaxies, this ratio must respect the equation:

$$\chi^2 + \left( \frac{\log\left[\frac{\gamma_D}{\gamma_0}\right]}{0.1} \right)^2, \tag{1}$$

where $\gamma_D$ is the mass-to-luminosity ratio, $\gamma 0$ is the expected ratio ($0.5(M_\odot/L_\odot)_{[3.6\mu m]}$) for the disk), such a ratio must respect the error in 1 $\sigma$ of 0.1 dex. For this purpose, a minimization fit $\chi^2$ was used that includes the mass-to-luminosity ratio *prior* Salucci et al. (2007). The dark matter density profiles used here are Burkert, NFW, Einasto and Isothermal. The circular velocities are given by:

**Burkert**

$$V^2(r) = G4\pi\rho_c r_c 3 \frac{\ln(1+\frac{r}{r_c}) - \frac{1}{2}\ln(1+(\frac{r}{r_c})^2)}{r}. \tag{2}$$

**NFW**

$$V(r)^2 = G4\pi\rho_0 r_s^3 \frac{\frac{r}{r_s} - \ln\left(1+\frac{r}{r_s}\right)}{r}. \tag{3}$$

**Isothermal**

$$V^2(r) = G4\pi\rho_s r_s 3 \frac{(\frac{r}{r_s}) - \arctan(\frac{r}{r_s})}{r}. \tag{4}$$

**Einasto**

$$V^2(r) = G4\pi r^3 \rho_s \frac{\exp(\frac{2}{\alpha})\exp(-\frac{2r^\alpha}{\alpha r_s^\alpha})}{3r}. \tag{5}$$

To decompose the contribution of the velocities of the data presented in Sofue (2020), we separate the Milky Way into Bulge, Disk and Halo.

For the Bulge, we adopt the exponential sphere model Sofue (2017) and Keeton (2014). This model describes the rotational speed as a function of the mass density $\rho$ as an exponential function of the radius $r$, with a scale parameter $a$, thus the speed is given by:

$$V_B^2(r) = \frac{GM_B(r)}{a}\left[\frac{1-e^{-x}\left(1+x+\frac{x^2}{2}\right)}{x}\right], \quad \text{where } x = \frac{r}{a}. \tag{6}$$

For the Disk, we use the exponential disk model (Sofue, 2017). For the exponential disk of finite thickness, where the density is given by a scale factor $b$ and a central density $\rho$, having the circular velocity given by:

$$V_D^2(r) = \frac{2GM_D(r)}{b} x^2 \left(I_0(x)K_0(x) - I_1(x)K_1(x)\right), \tag{7}$$

where $x = \frac{r}{b}$, and $I_i$ and $K_i$ are the Bessel functions for particular cases.

Each of the halo models exhibits different behaviors and was created in different circumstances under different conditions. For example, Burkert Burkert (1995) comes from observations, while NFW comes (Navarro, Frenk and White) from N-body simulations (Navarro, Frenk & White 1996). While the NFW profile predicts a dark matter density that increases continuously towards the center of spiral galaxies, the Burkert profile predicts a density that peaks at some point and then decreases smoothly. For the total velocity of the rotation curve is given by the sum of the squares of the individual contributions.

$$V^2 = \gamma_D V_D^2 + \gamma_B V_B^2 + V_{gas}^2 + V_{dm}^2. \tag{8}$$

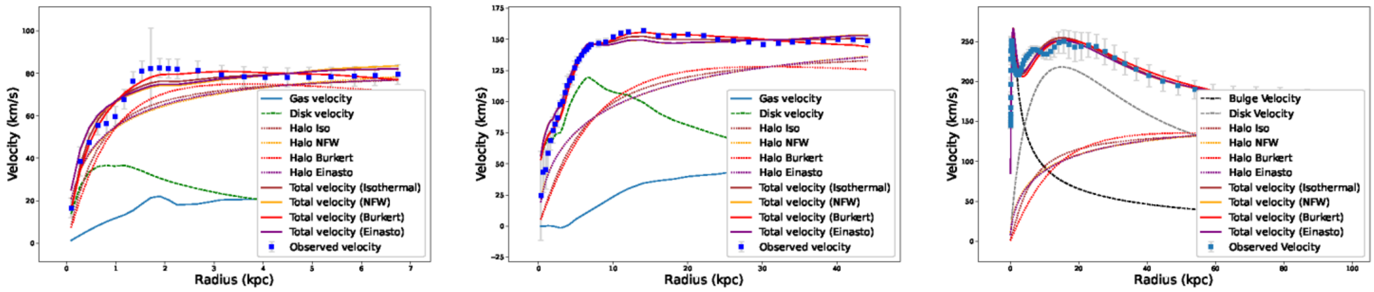


**Figure 1.** Rotation curves of the galaxies, UGC 05721 (left), NGC 3198 (middle) and the Milky Way (right). Data for UGC 05721 and NGC 3198 are from the SPARC catalogue Lelli et al. (2016), while those for the Milky Way are from Sofue (2020).

**Table 1.** Scale radius $r$ and mass density $\rho$ parameters obtained using minimization fitting through `Python` optimization algorithms, with $\gamma_D$ normalized for UGC05721 and NGC3198.

| | UGC05721 | | NGC3198 | | Milky Way | |
|---|---|---|---|---|---|---|
| | $r$ (kpc) | $\rho\left(\frac{M_\odot}{\text{kpc}}\right)$ | $r$ (kpc) | $\rho\left(\frac{M_\odot}{\text{kpc}}\right)$ | $r$ (kpc) | $\rho\left(\frac{M_\odot}{\text{kpc}}\right)$ |
| Burkert | 0.93 | $5.78\times10^{12}$ | 9.41 | $1.02\times10^{12}$ | 16.25 | $3.85\times10^{11}$ |
| NFW | 0.52 | $3.40\times10^{13}$ | 1.01 | $3.50\times10^{12}$ | 10.73 | $2.80\times10^{11}$ |
| Isothermal | 0.35 | $6.34\times10^{13}$ | 4.68 | $1.14\times10^{12}$ | 5.17 | $8.98\times10^{11}$ |
| Einasto | 6.87 | $4.53\times10^{11}$ | 12.50 | $4.92\times10^{9}$ | 152.53 | $3.14\times10^{9}$ |

The galaxies UGC05721 and NGC3198 extracted from the SPARC catalog do not have data related to the bulge, therefore their total velocity is given by:

$$V^2 = \gamma_D V_D^2 + V_{gas}^2 + V_{dm}^2. \qquad (9)$$

In the case of the Milky Way, the mass-to-luminosity ratio can be disregarded, and since the data extracted from Sofue Sofue (2020) do not have data on the gas contribution, the total velocity is given by:

$$V^2 = V_D^2 + V_B^2 + V_{dm}^2. \qquad (10)$$

It is also important to comment on the differences between the data used. The SPARC catalog Lelli et al. (2016) uses photometric data at $3.6\mu_m$ collected by the Spitzer Space Telescope to analyze the distribution of stellar mass in 175 nearby galaxies. These photometric data are complemented by rotation curves obtained from previous observations of atomic hydrogen (H I) and, in some cases, $H\alpha$. On the other hand, Sofue (2020) presents velocities from a variety of techniques, including radial velocity measurements of neutral hydrogen (H I), carbon monoxide (CO), OB stars, red giant stars, globular clusters, and parallax and proper motion measurements observed by VLBI and Gaia.

## 3. Results

Looking at the data extracted from the SPARC catalog with the model discussed here, we obtained for the galaxy $\gamma_D$ UGC05721 $\sim$ 0.56 and for NGC3198 $\sim$ 0.84. The table below presents the values of scale radius and density for each model:

Below are the comparative graphs for each of the three galaxies studied. For the galaxies extracted from the SPARC catalog $\gamma_D$ is already adjusted according to eq. 1.

For the Milky Way, the data presented up to $\sim$ 30 kpc are velocities of stars, from 30 kpc we have the velocities of atomic and molecular gas (see more in Sofue 2020).

## 4. Conclusions

We use a least-squares fit to obtain the best fit for the scale radius (kpc) and halo density parameters ($M_\odot$/kpc$^3$). We observe that the density profile that best fits the observational data is the Burkert profile, which is an empirical density function proposed to describe the distribution of dark matter in spiral galaxies. This halo has been evaluated in several studies and has been widely used by Salucci and collaborators Salucci et al. (2007). It is a spherically symmetric halo parameterized by two constants $\rho_c$ and $r_c$. For radii with $R >> r_c$ the density decays with $R^{-3}$ , while for small radii ($R << r_c$) the density is constant (Burkert, 1995). This profile tends to be more favored for smaller galaxies, with stellar masses of the order of $\sim 10^8 M_\odot$, as is the case of UGC 05721, but even large galaxies, with stellar masses of $\sim 10^{10} M_\odot$, also seem to favor this type of halo Rodrigues et al. (2017), as is the case of NGC3198 and the Milky Way. It is important to note that the present work is still under development, and the next steps consist of 1) Obtaining the best values for the free parameters using Bayes' theorem, 2) Extending the analysis presented for the galaxies UGC 05721 and NGC 3198 to the other galaxies in the SPARC catalog, and 3) Comparing our fits with those presented by Li and collaborators Li et al. (2018).

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