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Modeling the Mass Distribution in the Spiral Galaxy NGC 3198

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Abstract. We study the HI Rotation Curve of the spiral galaxy NGC 3198 in terms of mass decomposition. We model the Rotation Curve in the framework of different models for the Dark Matter distribution: the Burkert profile and NFW profile. We show that Universal Rotation Curve (Burkert halo+stellar disk+gas disk) fits data accurately. Instead, the NFW (NFW halo+stellar disk+gas disk) model gives non-physical values of NFW halo parameters.

1. Introduction

The existence of significant discrepancies in galaxy clusters between the visible mass and the dynamical mass has been discovered by Zwicky in 1933 [1]. He measured the radial velocities for a set of galaxies in the Coma cluster, computed the velocity dispersion and concluded, by using the virial theorem, that for such large velocity dispersions the total mass should be 50 times greater than the one derived from luminous matter in galaxies .

Later, in the 1970s by Rubin, Ford and Kent [2] was delivered the first reliable evidence for Dark Matter (DM) in form of non-Keplerian Rotation Curve (RC). They analysed an optical RC of the Andromeda galaxy. They were expecting to see the declining RC with $V \propto \frac{1}{\sqrt{R}}$, where V is the rotation velocity and R is the galactocentric distance. The expected RC is called the Keplerian RC, as an analogy to Solar system. However, this Keplerian decline was not observed but it was obtained an approximately flat RC. Therefore, they concluded that galaxies should be surrounded by great quantities of non-luminous matter distributed far beyond the visible part of galaxies in more or less spherically symmetric form. This is consistent with the idea of the existence of massive DM halos proposed, at the same time, by Ostriker and Peebles [3] in order to stabilize the cold self-gravitating axisymmetric disks against bar-like models.

Today many authors consider that the inner regions of galaxies contain little or no DM. It means that the observed baryonic matter is responsible for the RC only in the inner region (e.g. [4, 5, 6, 7]). In the outer part, however, we must add the DM halo. Investigation of the outer part of galaxies became possible thanks to the interpretation of the HI rotation curves by Bosma in 1978 [8].

In brief, nowadays it is commonly accepted that RCs of spirals and also other type of galaxies [9, 10, 11, 12] can be interpreted as evidence of the existence of this DM component. The distribution of DM in galaxies can be described by a theoretical or an empirical density distribution profile. The most adopted theoretical model of the DM density profile, based on

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numerical simulations of the formation of galaxies in the Cold Dark Matter (CDM) scenario in the expanding Universe, is the NFW model proposed by Navarro, Frenk and White [13]. ΛCDM scenario describes well the large-scale structure of the Universe (e.g. [14]), but it seems to fail on the scales of galaxies and it is not confirmed by observed data (e.g. [15, 16, 17]). Observations seem to indicate an approximately constant dark matter density in the inner parts of galaxies, while ΛCDM scenario indicates a steep power-law-like behaviour. This difference has become known as the "core-cusp problem" to solve which, many other empirical profiles, such as the pseudo-isothermal (ISO) DM halo model [18, 19] and the Burkert profile [20] have been considered.

In this paper we study the RC of a spiral galaxy NGC 3198 in order to derive the properties of the DM halo around the galaxy. Our analysis is based on HI observations published by Gentile et al. [22]: these observations are part of HALOGAS (Westerbork Hydrogen Accretion in LOcal GAlaxieS) survey. In this paper they derived a very extended RC out to 720 arcsec (correspond to 48 kpc for a distance at 13.8 Mpc) and their mass distribution was modelled in the framework of modified Newtonian dynamics (MOND). In this paper we model the RC in the framework of the NFW and the Burkert profiles.

This paper is organized as follows. In Sec.2 we model the RC by using the quadrature sum of the RCs of the individual mass components (stellar disk + Dark halo + gas disk) where for Dark halo we apply first the Burkert density profile, and then the NFW profile. In Sec. 3 we provide the mass modeling results. Our conclusions are drawn in Sec. 4.

2. Mass Modelling

The data presented in the paper [22] allow us to make use of the most extended RC of a galaxy ever measured, in terms of optical disk scalelength. We model the spiral galaxy NGC 3198 as consisting of two "luminous" components, namely the stellar and gaseous disks, embedded in a dark halo.

2.1. Luminous matter

In order to study the properties of luminous and dark matter in this galaxy, we can decompose the observed RC into the stellar disk, the bulge, gas and the DM halo:

$$V^2(r) = V_{\rm d}^2(r) + V_{\rm b}^2(r) + V_{\rm g}^2(r) + V_{\rm DM}^2(r). \tag{1}$$

$V_{\rm d}(r)$ is the contribution of the stellar disk, was taken from [21]. Here, we use $V_{\rm d}^2 = \frac{\Upsilon_*^{3.6}}{0.57} V_{deBlok}^2$, where V_{deBlok}^2 are the data from [21] and the stellar mass-to-light ratio $\Upsilon_*^{3.6}$ is a free parameter (taking into account the scaling factor 0.57).

$V_{\rm b}(r)$ is the contribution from the bulge component. In NGC 3198 can be indicated an additional (third) compact, central component, which can be considered as a bulge. However, how it was found by [21], adding this contribution will not change the results, therefore we assume $V_{\rm bulge}(r) = 0$.

$V_{\rm g}(r)$ is the helium corrected contribution of the gaseous disk derived from the HI surface density distribution by [22].

$V_{\rm DM}(r)$ is the contribution of the dark matter halo which we discuss below.

2.2. Dark matter

For the DM halo with the virial mass $M_{vir} = \frac{4}{3}\pi 100 \rho_{crit} r_{vir}^3$ several alternatives were investigated. In this paper we consider two of them.

2.2.1. Burkert halo Burkert ([23, 20]) proposed an empirical density distribution of dark matter:

$$\rho_{\rm B}(r) = \frac{\rho_0 r_{\rm core}^3}{(r + r_{\rm core})(r^2 + r_{\rm core}^2)}, \tag{2}$$

where ρ_0 (the central density) and $r_{\rm core}$ (the core radius) are the two free parameters.

2.2.2. Navarro, Frenk and White (NFW) halo Navarro et al. in 1996 [13] proposed a profile based on numerical simulations of the formation of galaxies in the CDM scenario. The NFW profile is written as

$$\rho_{\rm NFW}(r) = \frac{\rho_{\rm s}}{(\frac{r}{r_s})(1 + \frac{r}{r_s})^2}, \tag{3}$$

where $\rho_{\rm s}$ and r_s are respectively the characteristic density and the scale radius of the distribution. These two parameters are in principle independent, but they can also be expressed in terms of the virial mass $M_{\rm vir}$, the concentration parameter $c = \frac{r_{\rm vir}}{r_s}$ and the critical density of the Universe $\rho_{\rm crit} = 9.31 \times 10^{-30} {\rm g/cm}^3$ [24, 25]. By using Eq.(3), we can write:

$$\begin{aligned} \rho_s &= \frac{100}{3} \frac{c^3}{\log{(1+c)} - \frac{c}{1+c}} \, \rho_{\rm crit} \quad {\rm g/cm}^3; \\ r_s &= \frac{1}{c} \left(\frac{3 \times M_{\rm vir}}{4\pi 100 \rho_{\rm crit}} \right)^{1/3} \quad {\rm kpc}. \end{aligned} \tag{4}$$

The relation between $c - M_{\rm vir}$ is taken from [26]:

$$c \simeq 9.60 \left(\frac{M_{\rm vir}}{10^{12} (0.71)^{-1} M_\odot} \right)^{-0.075}. \tag{5}$$

3. Results

The results of mass decompositions are shown in Fig. 1 and Fig. 2.

We start from the results for the Burkert halo which gives a very good quality fit with a reduced chi-square value of $\chi^2 = 1.6$. The best-fit parameters of the Burkert halo are

$$\begin{aligned} \rho_0 &= (3.58 \pm 0.73) \times 10^{-25} \quad {\rm g/cm}^3; \\ r_{\rm c} &= (16.51 \pm 2.0) \quad {\rm kpc}; \\ \Upsilon_*^{3.6} &= (0.97 \pm 0.05). \end{aligned}$$

Then the dynamical mass of the stellar disk is

$$M_{\rm D} \simeq 1.1 \frac{\Upsilon_*^{3.6}}{0.57} V_{deBlok}^2(R_{\rm l}) \frac{R_{\rm l}}{G} \tag{6}$$

where V_{deBlok} is the contribution to the circular velocity of the stellar disk at a very extended point $R_{\rm l} \approx 48.2$ kpc. We found $M_{\rm D} \simeq 4.5 \times 10^{10} M_\odot$ with a propagated uncertainty of about 10 %. The corresponding virial mass and radius of the DM halo are $M_{\rm vir} = (5.7^{+1.3}_{-0.6}) \times 10^{11} M_\odot$ and $R_{\rm vir} = (212^{+11}_{-7})$ kpc as indicated above.

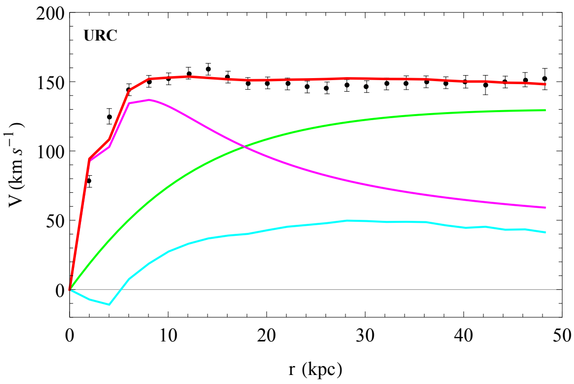

Figure 1. Burkert model of NGC 3198. The circular velocity data (filled circles with error bars) is modeled (thick Red line) with the Burkert profile (thick Green line), the disk (Magenta line) and the HI circular velocity (Azure line).

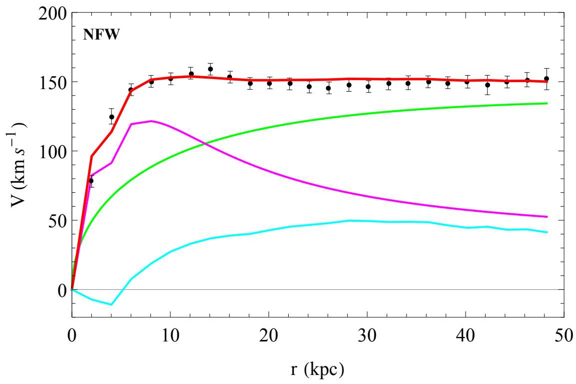

Figure 2. NFW model of NGC 3198. The circular velocity data (filled circles with error bars) is modeled (thick Red line) including the disk (Magenta line), the NFW halo profile (Green line) and the HI circular velocity (Azure line).

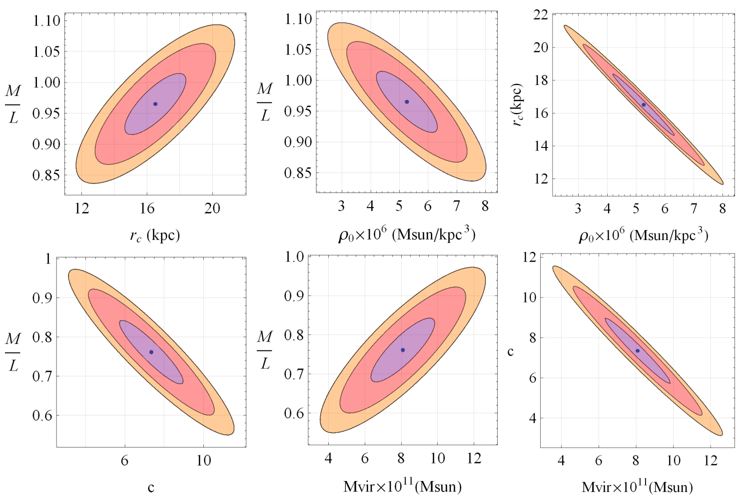

Figure 3. Top panel: 1, 2, 3σ confidence ellipses (Purple, Red, Orange respectively) for the best-fit parameters in the Burkert halo case. The central points indicate the best-fitting values, $r_{\rm c}$ is in units kpc, ρ_0 is in units $M_\odot/kpc^3$.
Bottom panel: 1, 2, 3σ onfidence ellipses (Purple, Red, Orange respectively) for the best-fit parameters in the NFW halo case. The central points, as well, indicate the best-fitting values, $M_{\rm vir}$ is in units $10^{11} M_\odot$.

For the NFW profile we fitted data in terms of the virial mass, the concentration parameter and the mass-to-light ratio $(M_{\rm vir}, c, \Upsilon_*^{3.6})$. In this case we have got the same value of a reduced chi-square, even slightly better, $\chi^2 = 1.5$. However, the value of the concentration parameter is inconsistent with the one found in Eq.(5), where $c \approx 10$. This discrepancy was found also in other works [27, 28].

In detail the results from the best-fit are

$$M_{\rm vir} \quad = \quad (8.1 \pm 1.8) \times 10^{11} \quad \mathrm{M}_\odot;$$

$$\begin{aligned} c &= (7.3 \pm 1.6); \\ \Upsilon_*^{3.6} &= (0.80 \pm 0.10). \end{aligned}$$

The corresponding values of the scale radius and the characteristic density are $r_\mathrm{s} = 32.9 \pm 9.7$ kpc and $\rho_\mathrm{s} = (9.9 \pm 5) \times 10^{-26}$ g/cm^3. The too high value of the scale radius r_s and the too low value of the characteristic density ρ_s are unrealistic.

The 1,2,3-σ confidence regions for the more relevant best-fit parameters are shown in Fig. 3. The central points correspond to the best-fit values.

4. Conclusions

We have used new HI observations of the spiral galaxy NGC 3198, performed by the HALOGAS survey, for the mass modeling. The HI disk of this galaxy is very extended, up to 13 disk length scale. The derived RC is dominated by DM at large galactocentric radii, where baryons are not able to account for the observed kinematics.

In this work we have used two DM profiles. The (cored) URC Burkert dark halo and NFW halo fit the data very well. However, the best-fit paremeters in NFW case are found outside the range expected in the ΛCDM scenario.

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