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On the non universality of surface density of galaxies

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We studied the correlation between the central surface density of dark matter haloes and the halo core radius of galaxy and galaxy recently studied on a wide range of scales. For this aim we used the secondary infall model, that we previously published, to get the halo density profile taking into account the effect of ordered and random angular momentum, dynamical friction, and adiabatic contraction of the dark matter due to the baryons collapse. We found that the column density within the halo characteristic radius r_* is not a universal quantity as claimed by other authors, but it correlates with the halo mass M_{200}. The scatter in the slope of the $S-M$ relation is 0.16 ± 0.05, leaving small room for the possibility of a constant surface density.

Key words: cosmology: theory, dark matter, large-scale structure of Universe

INTRODUCTION

An intriguing property of dark matter (DM) haloes was noted in [9]. Among other relations between the halo parameters, they found that the quantity $\mu_{0D} = \rho_0 r_0 \simeq 100 M_\odot/\mathrm{pc}^2$, proportional to the halo central surface density for any cored halo distributions, is nearly independent of the galaxy blue magnitude. Here ρ_0 and r_0 are, respectively, the central density and the core radius of the adopted pseudo-isothermal cored DM density profile. Donato et al. [7] confirmed this result (they found $\log \mu_{0D} = 2.15 \pm 0.2$, in units of $\log(M_\odot/\mathrm{pc}^2)$) and Gentile et al. [8] extended the result to the luminous matter surface density and found that the total luminous-to-dark matter ratio within one halo scale-length is constant. Opposite results were obtained in [3, 4, 11] where a systematic increase with luminosity L_V, the stellar mass M_* and the halo mass M_{200} was found, and it was shown that the DM column density, S, (defined in the following and equivalent to μ_{0D} in the case of fit with Burkert profile) is given by

$$\log S = 0.21 \log \frac{M_{halo}}{10^{10} M_\odot} + 1.79, \qquad (1)$$

with S in $M_\odot/\mathrm{pc}^2$.

In order to try to discriminate among these results and to find an explanation and analytical derivation of the surface density of halos, we analysed the problem using the secondary infall model (SIM) introduced in [6], taking into account ordered and random angular momentum, dynamical friction, and baryon adiabatic contraction.

THE MODEL AND THE S-M RELATION

The results discussed in the introduction claiming a constancy of the surface density [7, 8] of DM and those claiming a mass dependence [3, 4] are fundamentally based on fitting of observed properties of DM halos. With the exception of [2], no qualitative explanation and/or analytical derivation of the quoted results has been proposed so far. In what follows, we use a much more improved SIM not only taking into account angular momentum, but also baryons dynamical friction, and adiabatic contraction (see [6] for details). The model used to determine the density profiles of halos that we used to calculate the surface density of halos has been described in [6].

In [7, 8] the rotation curves and weak lensing data for a sample of dwarf, spiral and elliptical galaxies fitted by the Burkert profile were analysed. The fit of the rotation curves yields the values of the two structural DM parameters (i. e., r_0, central radius, and ρ_0, central density), then the surface density is calculated as $\mu_{0D} = \rho_0 r_0$. Boyarsky et al. [3] extended the analysis of [7, 8] to galaxies and galaxy clusters and fitted the DM profiles by means of three DM profiles models, namely Burkert profile, pseudo-isothermal profile (ISO), and Navarro–Frenk–White (NFW) profile. Cardone & Tortora [4] used two DM

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profiles for the fit, namely Burkert profile and ISO.

Another way of determining the surface density, more general than that used by [7, 8] (in the case one uses more than one model density prole for the fit), is to introduce a dark matter column density, averaged over the central part of an object:

$$S = \frac{2}{r_\star^2}\int_0^{r_\star} rdr \int dz \rho_{DM}\left(\sqrt{r^2+z^2}\right). \quad (2)$$

Integral over z extends to the virial boundary of a DM halo. The definition (2) implies that S is proportional to the DM surface density within $r_\star$ ($S \propto \rho_\star r_\star$). However, the quantity S is more universal, as it is defined for any (not necessarily cored) DM profile.

In Fig. 1 we plot $\mathcal{S}(r_s)$ vs. M_{200} for our model and for results obtained by different authors. From bottom to top: the dotted line represents the best fit linear relation using the fit from [5], while the solid line denotes the direct fit methods, obtained in [4]; the long–short dashed line represents $\mathcal{S}(r_s)$ obtained with the model described in the present paper; the short–dashed line represents prediction and the results from the ΛCDM N–body simulation of [10]; the long–dashed line represents the best fit linear relation from [3]; the dot–dashed line represents the secondary–infall model [2] prediction.

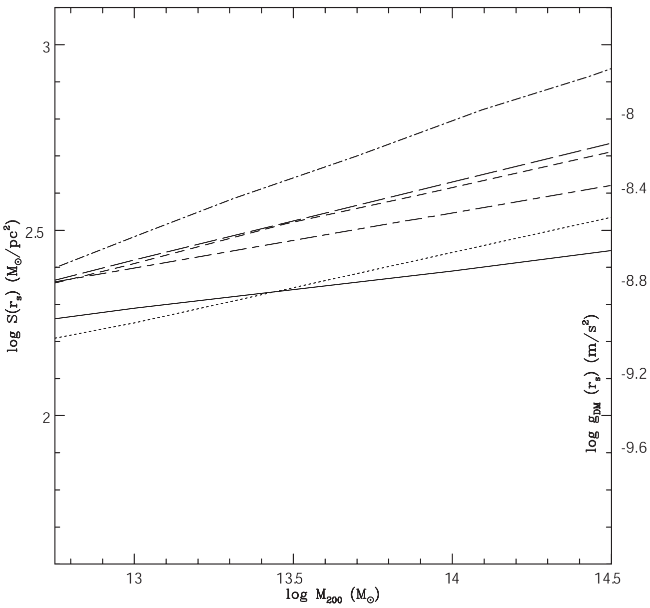

Fig. 1: $\mathcal{S}(r_s)$ as a function halo mass M_{200}. See explanation in the text.

The maximum likelihood fit for the correlation $\log\mathcal{S}(\nabla_f)$-$\log M_{200}$ in our model is

$$\log\mathcal{S}(r_s) = 0.16\log\left(\frac{M_{200}}{10^{12}M_\odot}\right) + 2.23. \quad (3)$$

The marginalized constraints on the scaling relations parameters for the correlation involving $\mathcal{S}$ in our model is $\log\mathcal{S}(r_s)$-$\log M_{200}$ $0.16^{+0.05}_{-0.05}$, while in the case of [4], assuming a fiducial NFW+Salpeter model, it is $\log\mathcal{S}(r_s) - \log M_{200}$ $0.14^{+0.15}_{-0.15}$ and $\log\mathcal{S}(r_s) - \log M_*$ $0.29^{+0.15}_{-0.15}$.

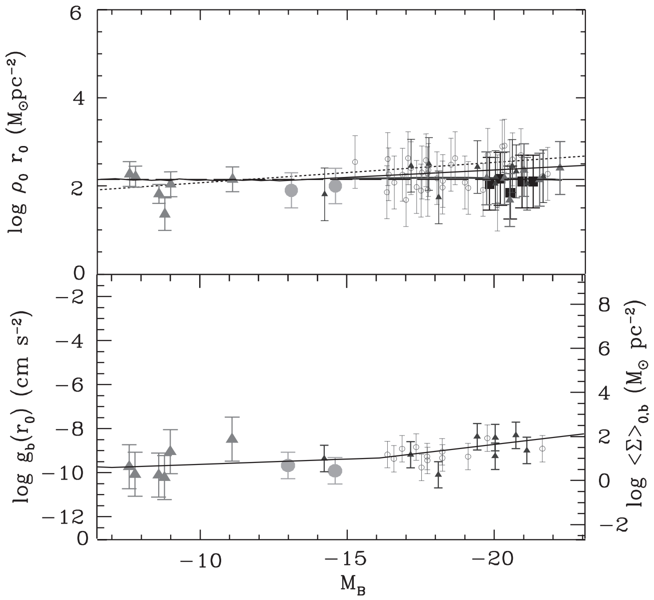

Fig. 2: Top: $\rho_0 r_0$ in units of $M_\odot/pc^2$ as a function of galaxy magnitude for different galaxies and Hubble Types. See explanation in the text.

In Fig. 2 we compare the result of the present model with [7] and [8] results. The top panel of Fig. 2 shows $\rho_0 r_0$ in units of $M_\odot/\mathrm{pc}^2$ as a function of galaxy magnitude for different galaxies and Hubble types: results from [12] (empty small circles), the universal rotation curve (URC, solid line), the dwarf irregulars (full circles) N 3741 ($M_B = -13.1$) and DDO 47 ($M_B = -14.6$), spirals and ellipticals investigated by weak lensing (black squares), dSphs (big triangles), nearby spirals in the HI Nearby Galaxy Survey (THINGS, small triangles), and early-type spirals (intermediate triangles). The long dashed line is the result of [7], the solid line is the result of the present paper when taking into account all effects considered in [6], the dashed line represents the result of surface density considering galaxies are made only of dark matter, the dotted line is the result of N-body simulations from [3]. Bottom pannel of Fig. 2 shows $< \Sigma >_{0,b}$ and $g_b(r_0)$ as a function of the B-band absolute magnitude of the galaxies. From the original sample of [7], here, as in [8], are used the dwarf spheroidals data, NGC 3741, DDO 47, and the two samples of spiral galaxies [1, 12] which all together span the whole magnitude range probed in the original sample [7]. The big triangles are the dwarf spheroidal galaxies, the left full circle is NGC 3741 and the right full circle is DDO 47, and the empty circles and small triangles are the [12] and THINGS spiral galaxies samples, respectively. For masses smaller than $\simeq 5 \times 10^{10} M_{\odot}$ the surface density is constant while for larger masses there is a mass dependence ($S \propto M^{0.16}$). The result of the present paper for $S - M$ is consistent with [7] and [8] results for small masses, but at the same time shows a clear dependence on mass of larger objects, contradicting [7] and [8] claim of a universal surface density of halos in a very wide mass range. The previous results evidence limits of the Modified Newtonian Dynamics (MOND). Gentile et al. [8] found that the acceleration generated by baryonic matter at r_0, $g_b(r_0)$, is constant, similarly to a_0. Since the surface density is proportional to g_b it must be constant, too. In Fig. 2 (bottom panel) we show that the surface density has a similar behaviour to that predicted in [8] till a given M_B and after it the surface density starts to increase. This means that $g_b(r_0)$ is not universal, but depends on magnitude and mass. In summary, our result shows that MOND is working well in the case of dwarf galaxies and spirals, but going further with mass it does not work well.

CONCLUSIONS

Using the SIM model introduced in [6], we studied the correlation between the central surface density and the halo core radius of galaxy and galaxy cluster DM haloes. Differently from what claimed in [7] and [8], the column density within the halo characteristic radius r_* is not a universal quantity. The surface density obtained, $S \propto M^{0.16 \pm 0.05}$ leaves small room for the possibility of a constant surface density, as claimed by the previous cited authors.

The non self–similar behaviour of the surface density and acceleration generated by baryons, $g_b(r_0)$ shows that while MOND paradigm is finely working for dwarfs and spirals of small mass, it has increasing difficulties with increasing mass.

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