Boletim da Sociedade Astronômica Brasileira, **34**, no. 1, 82-83
© SAB 2023

Indirect searches for dark matter with gamma-ray telescopes

J. Mamprim & V. de Souza

[1] Instituto de Física de São Carlos, Universidade de São Paulo. e-mail: juliagouveamamprim@usp.br, vitor@ifsc.usp.br

Abstract. We analysed the rotation velocity curves of 156 galaxies included in the SPARC (Spitzer Photometry and Accurate Rotation Curves) data set in order to investigate dark matter distribution models through the fitting of density function's parameters, concluding that the Einasto profile has shown better results for our galaxy sample. This study may help us to explore the potentialities of gamma astronomy observatories (specially the Cherenkov Telescope Array) regarding the indirect detection of dark matter, for it is possible to simulate the gamma rays sign that is expected from one or multiple density profiles studied, once we define the function's parameters.

Resumo. Analisamos as curvas de velocidade de rotação de 156 galáxias presentes no conjunto de dados do SPARC (Spitzer Photometry and Accurate Rotation Curves) a fim de investigar modelos de distribuição de matéria escura através do ajuste dos parâmetros de funções densidade, concluindo que o perfil Einasto apresentou melhores resultados para o nosso conjunto de galáxias. Este estudo pode nos ajudar a explorar as potencialidades dos observatórios de astronomia gama (especialmente o Cherenkov Telescope Array) no que diz respeito à detecção indireta de matéria escura, sendo possível simular o sinal de raios gama esperado a partir de um ou múltiplos perfis de densidade aqui estudados, uma vez definidos os parâmetros das respectivas funções.

Keywords. dark matter – halo – Gamma rays

1. Introduction

Dark Matter (DM) is believed to be a neutral, stable and non-baryonic elementary particle that does not belong to the Standard Model and accounts for about 85% of the Universe's matter content. In high density environments of the Universe, DM may self-annihilate producing a strong gamma-ray signal.

The first evidence of dark matter existence arised from the observed rotation velocity curves of galaxies. Experimental data show that the usual decay with $r^{-1/2}$ is not verified as we increase the distance from the galaxy nuclei, strongly suggesting the presence of a DM halo contributing to the gravitacional effect as to prevent the rotation velocity to decay with distance. Describing the DM mass distribution within the halo leads to the study of several density profiles that play a crucial role on determining fundamental DM particles properties such as mass and annihilation cross section, allowing us to predict which gamma-ray signal should be expected given a theoretical particle model. Under this scope, gamma-ray observatories may be able to detect dark matter, with the Cherenkov Telescope Array (CTA) presenting the most promising results perspective, once it will be around ten times more sensitive than its predecessors and have unprecedented accuracy in its detection of high-energy gamma rays.

2. Methods

2.1. Density profiles

We investigate four dark matter density profiles very common in literature: pseudo-isothermal, NFW (Navarro, Frenk and White), Burkert and Einasto. In general, these profiles present two parameters of interest: a scale radius r_s and a volume density ρ_s, characteristic for each galactic halo. It is convenient to express r_s as $r_s = r_{200}/C_{200}$, with r_{200} refered as the virial radius of the system and C_{200} as a dimensionless parameter known as the halo's concentration. Now, for the density parameter, we have $\rho_s = \delta_s \rho_c$, where ρ_c is the critical density of the Universe $\rho_c = 3H^2/8\pi G$ (H is the current value of Hubble's constant) and δ_s is the characteristic overdensity of the halo. One must have in mind that r_{200} determines the total mass of the halo, $M_{200} = 200\rho_c 4\pi r_{200}^3$, and that δ_c and C_{200} are related by the requirement that the mean density within r_{200} should be $200\rho_c$. In the following, we describe four DM halo density models.

Pseudo-isothermal: this is a very simple empirical profile with a constant-density core

$$\rho_{\rm pISO} = \frac{\rho_s}{1 + \left(\frac{r}{r_s}\right)^2}. \tag{1}$$

Defining the dimensionless parameter $x = r/r_s$, we can write the corresponding rotation velocity profile,

$$V^2_{\rm pISO} = V^2_{200} \frac{C_{200}}{x} \left[\frac{x - \arctan(x)}{C_{200} - \arctan(C_{200})} \right]. \tag{2}$$

NFW: this cuspy profile was derived from N-body DM-only simulations of halo structure formation (Navarro, Frenk & White 1996),

$$\rho_{\rm NFW} = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}. \tag{3}$$

Again, we can write it's corresponding rotation velocity function

$$V^2_{\rm NFW} = V^2_{200} \frac{C_{200}}{x} \left[\frac{\ln(1+x) - x/(1+x)}{\ln(1+C_{200}) - C_{200}/(1+C_{200})} \right]. \tag{4}$$

Burkert: Burkert (1995) proposed to modify the pseudo-isothermal profile in order to force its enclosed mass to diverge more slowly,

$$\rho_{\rm Bkrt} = \frac{\rho_s}{(1 + \frac{r}{r_s})[1 + (\frac{r}{r_s})^2]}, \tag{5}$$

with the rotation velocity function given by

$$V_{\rm Bkrt}^2 = V_{200}^2 \frac{C_{200}}{x} \left[\frac{\frac{1}{2}\ln(1+x^2) + \ln(1+x) - \tan^{-1}(x)}{\frac{1}{2}\ln(1+C_{200}^2) + \ln(1+C_{200}^2) - \tan^{-1}(C_{200})} \right]. \quad (6)$$

Einasto: According to high-resolution DM-only simulations, a good description of galaxy halos is given by the Einasto (Einasto 1965) profile,

$$\rho_{\rm Einasto} = \rho_{\rm s} \exp\left\{ -\frac{2}{\alpha}\left[\left(\frac{r}{r_{\rm s}}\right)^{\alpha} - 1\right]\right\}, \quad (7)$$

where we introduce the adicional shape parameter α. Einasto's velocity curve is then given by Merritt (2006).

$$V_{\rm Einasto}^2 = V_{200}^2 \frac{C_{200}}{x} \frac{\Gamma(\frac{3}{\alpha}, \frac{2}{\alpha}x^{\alpha})}{\Gamma(\frac{3}{\alpha}, \frac{2}{\alpha}C_{200}^{\alpha})}, \quad (8)$$

where $\Gamma(a, x) = \int_0^x t^{a-1}e^{-t}dt$ is the incomplete Gamma function.

2.2. Galaxy sample and curve fitting

All experimental data referring to the rotation curves of galaxies used in this work can be found in the SPARC database (*Spitzer Photometry and Accurate Rotation Curves*) (Lelli, McGaugh & Schombert 2016), a catalog containing information on the rotation velocity of 175 galaxies among spirals and irregulars, of which 156 galaxies were selected due to quality markers. The galaxies had their baryonic mass profiles analyzed by the SPARC team according to the structural components of the stellar disc, gas and bulge. The decomposition of the total rotation velocity into its baryonic components follows from the analysis of mass profiles obtained by *Spitzer* using photometry in the infrared region (3.6μm) and from spectral measurements of the HI/Hα emission line of the intergalactic gas.

The velocity relative to the dark matter component can be obtained from the expression

$$V_{\rm DM} = \sqrt{V_{\rm obs}^2 - \Upsilon_{\rm d} V_{\rm d}^2 - \Upsilon_{\rm b} V_{\rm b}^2 - V_{\rm g}^2}, \quad (9)$$

where $V_{\rm d}$, $V_{\rm b}$ and $V_{\rm g}$ are the rotation velocities of the disc, bulge and gas components, respectively, and the parameters $\Upsilon_{\rm d}$ and $\Upsilon_{\rm b}$ (Li, Lelli, McGaugh & Schombert 2020) are the mass/luminosity ratios for the stellar components, whose contributions are tabulated in the SPARC catalog according to the mass/luminosity ratio of the Sun. We can fit the function $V(r)$ to data determining the constants $r_{\rm s}$ and C_{200} for the four density models explored, in addition to α for the Einasto profile. In order to perform the fit, we used the `iminuit` library, a Python interface for C++ `Minuit2` (James & Roos 1975), maintained by the CERN ROOT team and designed for likelihood and least-squares fits of parametric models to data.

3. Results

We found the best-fit parameters and calculated the respective p-value for the 156 galaxies. Figure 1 shows the DM curve fit for the spiral galaxy UGC02953, according to the Einasto profile. The p-value cumulative distribution function of the 156 galaxies for each DM halo profile (in comparison to an imposed baryonic-only keplerian model) is shown in Figure 2. Here, we consider that a p-value lower than 0.05 shall lead to the rejection of the model.

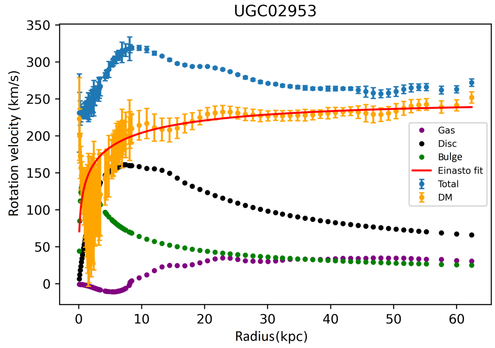

Figure 1. Einasto fit; p-value = 0.99; $r_{\rm s}$ = (56.46 ± 5.07) kpc; C_{200} = 35.55 ± 1.77; α = 0.10 ± 0.06;

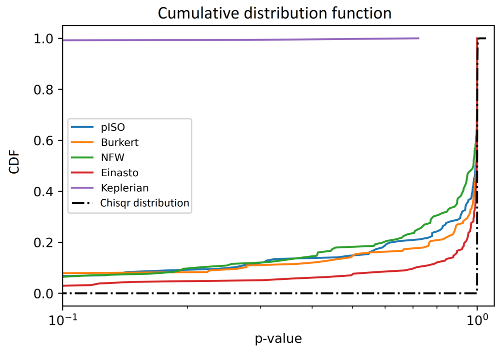

Figure 2. Normalized cumulative distribution function of the p-value for the 156 galaxies according to the each model.

Of the 156 galaxies, 10 presented a p-value below 0.05 for the Burkert profile, 8 for the pseudo-isothermal, 8 for the NFW and only 2 for the Einasto. In addition, an adjust of the $V_{\rm bar}$ component to a keplerian density model was performed. Attempting to relate this curve to $V_{\rm obs}$ resulted in a p-value smaller than 0.05 for 154 of the 156 galaxies, indicating that this model does not describe the data and therefore should be rejected.

4. Conclusion

Refering to our galaxy sample, the Einasto density profile proved to be the most adequate within the parametric fits performed in this work. Despite that, the pseudo-isothermal, NFW and Burkert models can not be disregarded as a representation of our data, since for most cases they presented a p-value superior to 0.05. We also conclude that the total rotation velocity observed in galaxies is not, in general, consistent with the total velocity of the baryonic components only, requiring the presence of a dark matter halo, as expected.

Acknowledgements. This project (2021/01089-1 & 2022/02102-4) was supported by FAPESP.

References

Burkert, A. 1995, ApJL, 447, L25
Einasto, J. 1965, Trudy Astrofizicheskogo Instituta Alma-Ata, 5, 87
James, F. & Roos, M. 1975, Comput. Phys. Commun., 10, 343
Lelli, F., McGaugh, S. S., & Schombert, J. M. 2016, AJ, 152, 157
Li, P., Lelli F., McGaugh, S. & Schombert, J. 2020, The Astrophysical Journal Supplement Series, 247, 31
Merritt, D., Graham, A. W., Moore, B., Diemand, J., & Terzić, B. 2006, AJ, 132, 2685
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563