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Memorie della

Dark Matter Cigars

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Abstract. We report that prolate, cigar-shaped dark matter haloes, or equivalent elongated gravity sources, provide a good fit to the galaxy rotation curve $v(r)$ (that flattens at large r). Unlike spherical haloes with specific functional dependences of the r density distribution $\rho(r) \propto 1/r^2$ when $v(r) \simeq$ constant, prolate haloes generically produce flat rotation curves independently of such radial distributions. This is because constant circular velocity curves, in the limit $r \to \infty$, naturally follow from a cylindrical/filamentary source as an extreme case of prolateness.

Key words. Galactic rotation curves – Dark matter haloes – Elongated/prolate haloes

1. Introduction

We summarize ongoing work Bariego Quintana (2022); Bariego Quintana et al. (2022) fitting SPARC galactic rotation data Lelli et al. (2016), and report that galactic-scale prolate dark matter (DM) haloes provide overall better fits, for generic DM density profiles different from the isothermal $1/r^2$ one, than spherical or oblate haloes.

This is perhaps unsurprising in view that exactly flat rotation curves $v(r) =$ constant are a limit described by exactly filamentary sources of gravity Llanes-Estrada (2021) and that prolate haloes seem to be a majority of those produced by cosmological simulations Allgood et al. (2006); Flores et al. (2007). Such simulations have found numerical evidence for distorted DM haloes, with prolateness prefered over oblateness and spherical symmetry. Our work exposes that this shape distortion of haloes is a possible culprit for the constant $v(r)$ galaxy rotation curves that have been known for decades Rubin et al. (1980).

2. Methods

The density profile employed for the DM halo (see figure 1) is a symmetric, uniform top with a sharp edge,

$$\frac{\rho(r,\theta)}{\rho_0} = \theta\left(r - \sqrt{\left(\frac{\cos^2\theta}{a^2} + \frac{\sin^2\theta}{b^2}\right)^{-1}} \right), \quad (1)$$

but other profiles have been tested Bariego Quintana et al. (2022). The difference is immaterial as concerns the shape. In Figure 1 we show how prolate haloes naturally have flatter rotation curves far outside the visible matter distribution. Far away from the dark matter halo itself, only the first (mass) term in a multipole shape expansion is relevant, and all compact objects should return to the Keplerian

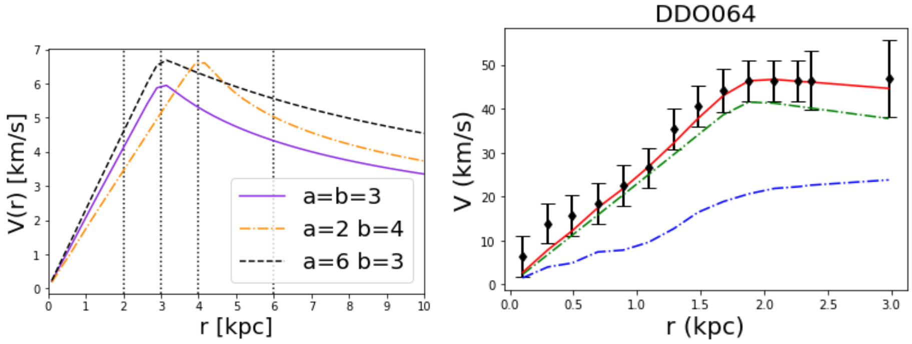

Fig. 1. Left plot: rotation curves $v(r)$ due to spheroidal DM sources of different shapes. The prolate one produces a curve (top dashed line) that falls–off with r much more slowly than a spherical one (solid bottom line, purple online) and even more so than an oblate halo, that falls the fastest once its maximum has been reached (middle, dot-dashed curve, orange online). **Right plot:** fit, with $\chi^2 = 0.37$, to the velocity curve of a typical galaxy DDO064 with $v(r)$ measured by SPARC. It yields a prolate halo with major semiaxis $a = 5.38(7)$, minor semiaxis $b = 1.85(1)$ (and density $\rho_0 = 100$ kpc^{-2} in geometrized units with $G = 1$), showing $a > b$ and therefore a clear prolate shape. The bottom dashed-dotted line (blue online) is the contribution from visible baryon matter as reported by SPARC. The next line up (green online) represents our fit DM contribution, and the solid line is the sum of both.

$v \propto \sqrt{r}$ curve: an infinite cylinder would instead have a flat $v(r)$ to arbitrary distance.

3. Results and conclusion

We have produced extensive fits with multipolar expansions of either $\rho(r, \theta)$ or the gravitational potential itself to the (mostly) spiral galaxy rotation data, and confirm the intuition that prolate shapes should generally provide a better description of the observations. Additionally, prolate haloes normally require less fine tuning than spherically-shaped ones.

The resulting model ranking of table 1) shows that prolateness prefered (the exception being shapes near $v \propto 1/r^2$ for which sphericity already yields $v(r) =$ constant.

In summary, because the rotation curves are intensely used to test DM models Khelashvili et al. (2022) at the galactic scale, we think it is important to note the very large effect that the shape of the halo not being spherical has on the rotation curve.

Our contribution is to note that this prolateness alone can drive the empirical rotation curves to $v(r) \to$ constant flattening, making the fine detail of the radial DM distribution less important (and also less informative about the underlying DM interactions and granularity).

Table 1. Average and median ranking of various DM haloes or alternatives, as judged by SPARC data. The purely Newtonian $v(r)$ with visible matter only yields the worst fits. The (spherical) Einasto and (cylindrical) log dark matter potentials rank best, showcasing a shape/profile degeneracy: a spherical profile containing a $\rho \propto r^{-2}$ piece, or a generic profile with prolate shape, are both competitive.

Model	$\bar{x} \pm \sigma$	Median
Gen. log(r) (cylindrical)	2.4 ± 1.9	2 ± 1
Spherical Einasto	3.1 ± 1.6	3 ± 1
Woods-Saxon cylinder	3.7 ± 1.9	3 ± 1
Pseudo-Isothermal	4.5 ± 1.5	4 ± 1
MOND Simple	4.9 ± 2.1	6 ± 1
MOND Standard	5.4 ± 2.2	6 ± 1
Finite-width cylinder	5.8 ± 2.4	7 ± 1
Spherical NFW	6.5 ± 1.7	7 ± 1
Newtonian	8.6 ± 1.4	9 ± 0

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