

The radial acceleration relation and its emergent nature

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Abstract. We review some of our recent results about the Radial Acceleration Relation (RAR) and its interpretation as either a fundamental or an emergent law. The former interpretation is in agreement with a class of modified gravity theories that dismiss the need for dark matter in galaxies (MOND in particular). Our most recent analysis, which includes refinements on the priors and the Bayesian test for compatibility between the posteriors, confirms that the hypothesis of a fundamental RAR is rejected at more than 5σ from the very same data that was used to infer the RAR.

Keywords. galaxies: kinematics and dynamics, dark matter, gravitation

1. Introduction

The Radial Acceleration Relation (RAR) (McGaugh *et al.* 2016) shows a sharp correlation between two accelerations associated to galaxy rotation curves. Since this correlation with its small dispersion is not an obvious outcome of the standard dark matter picture, several works interpreted the RAR as evidence for modified gravity such as the Modified Newtonian Dynamics (MOND) (e.g., Li *et al.* 2018). For the latter model, such correlation is a fundamental property of gravity, which is achieved by introducing a fundamental acceleration scale a_0 , while removing dark matter.

Rodrigues *et al.* (2018a) have shown, using Bayesian inference and the SPARC data (Lelli *et al.* 2016), that the a_0 credible intervals for different galaxies are not compatible among themselves at more than 10σ . Hence, also considering that high-quality rotation curve data were used, this led to a re-interpretation of the RAR as the strongest evidence against MOND as a gravitational theory (Marra *et al.* 2020). Here we consider the approach of Rodrigues *et al.* (2018a) together with further recent refinements by Marra *et al.* (2020) on the statistical analysis.

To evaluate if MOND works as a dark matter replacement in galaxies, one has to address the issue of finding a_0 . A common practice is to fit many galaxies and take the median of the best-fit values. Doing so is not optimal since it neglects the information from the a_0 posterior distributions of the individual galaxies (i.e., the “errors” on a_0 for each one of the galaxies). Moreover, and most importantly, from those posteriors one can test if the observational data are compatible with the existence of a common a_0 value. If they are not compatible, then a_0 is not fundamental and the RAR is necessarily an emergent correlation. Assuming standard dark matter, the RAR must be emergent (see e.g., Stone & Courteau 2019). If the RAR is emergent it can be useful (like many other emergent correlations), but it cannot directly reflect a fundamental property of gravity.

Table 1. The rejection level of the fundamental a_0 hypothesis.

Method	RAR sample (153 galaxies)	\mathcal{S}_2 subsample (91 galaxies)
Monte Carlo χ^2 test	$> 5.7\sigma$	5.3σ

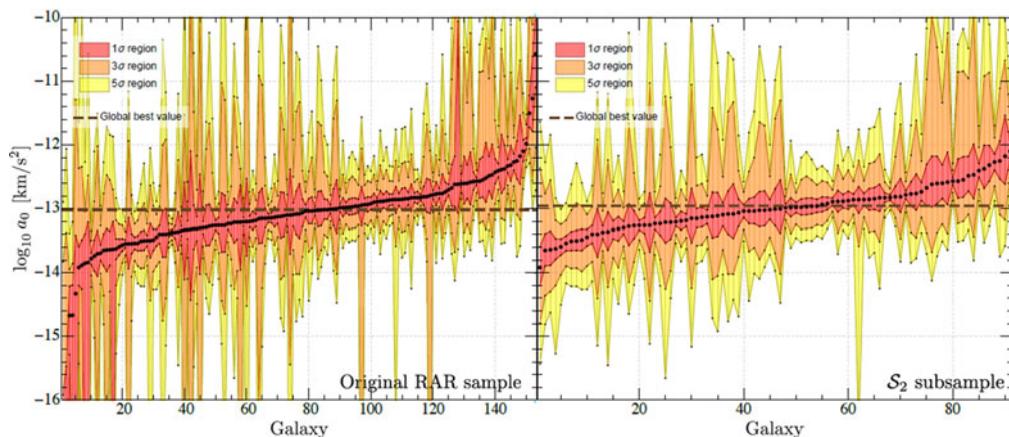


Figure 1. The a_0 modes (black dots) and the 1σ , 3σ and 5σ credible intervals for each one of the galaxies. The left panel shows all the 153 RAR galaxies, while the right panel shows a subsample (\mathcal{S}_2) with a stronger quality cut: galaxies with too high χ^2_{\min} values are also eliminated (91 galaxies are left). See Marra *et al.* (2020) for further details.

2. Methods and Results

Marra *et al.* (2020) improved the methodology of Rodrigues *et al.* (2018a) by considering priors more closely related to the observational uncertainties (see also Rodrigues *et al.* 2018b). A summary of the results from Marra *et al.* (2020) is shown in Table 1 and Fig. 1. Beyond the variation of a_0 from galaxy to galaxy, it is also considered the variation of mass-to-light ratios, distances and inclinations. Another improvement concerns the comparison of the credible intervals, since the method no longer employs Gaussian approximations (see also Cameron *et al.* 2020; Rodrigues *et al.* 2020). In particular, the existence of a common a_0 value is tested using the χ^2 statistics, an extension of the tension estimator of Verde *et al.* (2013), which is based on the Bayes factor.

We conclude with our opinion on MOND: historically it has stimulated relevant developments for galaxy astrophysics. As an effective theory for galaxy dynamics valid on average, it is useful and it is the RAR (i.e., a correlation between accelerations). As a theory for gravity, it has many problems, even for galaxy rotation curves.

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References

- Cameron, E., Angus, G. W., Burgess, J. M., *et al.* 2020, *Nat. Astron.*, 4, 132
 Lelli, F., McGaugh, S. S., Schombert, J. M., *et al.* 2016, *AJ*, 152, 157
 Li, P., Lelli, F., McGaugh, S., Schombert, J., 2018, *Astron. Astrophys.*, 615, A3
 Marra, V., Rodrigues, D. C., de Almeida, Á. O., 2020, *MNRAS*, 2002.03946

- McGaugh, S., Lelli, F., Schombert, J., 2016, *Phys. Rev. Lett.*, 117, 201101
- Rodrigues, D. C., Marra, V., Del Popolo, A., Davari, Z., *et al.* 2018a, *Nat. Astron.*, 2, 668
- Rodrigues, D. C., Marra, V., Del Popolo, A., Davari, Z., *et al.* 2018b, *Nat. Astron.*, 2, 927
- Rodrigues, D. C., Marra, V., Del Popolo, A., Davari, Z., *et al.* 2020, *Nat. Astron.*, 4, 134
- Stone, C. & Courteau, S. 2019, *ApJ*, 882, 6,
- Verdem L., Protopapasm P., Jimenez R. 2013, *Phys. Dark Univ.*, 2, 166