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GALAXY CLUSTERS IN MOND: THE CASE OF ULTRA DIFFUSE GALAXIES IN THE COMA CLUSTER

S. T. Nagesh[1], J. Freundlich[1], B. Famaey[1] and M. Bilek[2]

Abstract. Modified Newtonian dynamics (MOND) postulates a deviation from Newtonian gravity in the low acceleration regime. It is an alternative to dark matter that enjoys much success on galaxy scales, but not on galaxy cluster scales. A fundamental aspect of this paradigm is the violation of the strong equivalence principle (SEP). The SEP states that the internal dynamics of a system, on scales much smaller than the variations of the external gravitational field itself, should be independent of this external field; its violation induces that galaxies experiencing an external field should behave differently than their isolated counterparts. Observations of ultra-diffuse galaxies (UDGs) in galaxy cluster environments provide an opportunity to test MOND in the presence of an external field, especially since UDGs have significantly low internal acceleration. Recent work compared the line-of-sight stellar velocity dispersions of 11 UDGs in the Coma cluster and found that they were higher than the MOND predictions including the external field effect. Tidal forces in the cluster environment may provide an explanation for this discrepancy. Here, we present 36 simulations of Coma cluster UDGs launched from different distances from the center on different orbits in the MOND framework to test if tidal heating can inflate the velocity dispersion to match the observations. We find that tidal disruption near the cluster center renders inadequate to inflate the velocity dispersion of these UDGs to the observed levels whilst retaining their structural properties. This sets interesting constraints on any further development of the paradigm.

Keywords: gravitation - dark matter - galaxies: evolution - galaxies: clusters: general - galaxies: clusters: individual: Coma - galaxies: kinematics and dynamics

1 Introduction

Modified Newtonian Dynamics (MOND), proposed by M. Milgrom in 1983 (Milgrom 1983b) in an attempt to circumvent the then incipient dark matter paradigm, postulates that systems with Newtonian gravitational accelerations $g_N < a_0$, where $a_0 = 1.2 \times 10^{-10}$ ms^{-2} (Gentile et al. (2011)) deviate significantly from Newtonian behaviour. Under these conditions, the true gravity g will essentially be $g = \sqrt{a_0 g_N}$, where g_N is the Newtonian acceleration.

MOND has been surprisingly successful over the years in explaining many galactic scale phenomena, like the detailed shape of galaxy rotation curves using just the baryonic matter distribution of the galaxy. It accounts for wiggles (also known as Renzo's rule) observed in the rotation curves (Sancisi (2004); Famaey & McGaugh (2012); Banik & Zhao (2022)). MOND has been successful in predicting various scaling relations such as the baryonic Tully-Fisher relation (BTFR; Milgrom (1983a)) and its local analogue, the radial acceleration relation (RAR) which relates acceleration due to baryons g_{bar} with the dynamical observed acceleration g_{obs} at all radii (McGaugh (2016); Lelli et al. (2017)).

A fundamental aspect of the modified gravity version of MOND is the 'external field effect' (EFE), which is a manifestation of the breaking of the strong equivalence principle (SEP) in this paradigm. In simple words, if a system with internal acceleration g is embedded in a constant external gravitational field g_e such that $g < g_e$, then the external field effect influences the internal dynamics of the system. The internal acceleration of such a system deviates from the isolated MOND case ($g = \sqrt{a_0 g_N}$) towards a Newtonian behaviour ($g \propto g_N$), which should have a signature in observations and can thus be tested. For example, any rotationally (or pressure)

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[1] Université de Strasbourg, CNRS, Observatoire astronomique de Strasbourg, UMR 7550, F-67000 Strasbourg, France
[2] LERMA, Observatoire de Paris, CNRS, PSL Univ., Sorbonne Univ., 75014 Paris, France

supported isolated galaxy with $g < a_0$ should exhibit a MOND behaviour and fall on the RAR, while systems under the influence of the EFE should deviate from the RAR. The isolated systems should indeed have a higher rotational velocity (velocity dispersion) as compared to their counterparts around a massive host with a strong external field. This is however true only at equilibrium.

Ultra diffuse galaxies (UDG) are very low-surface brightness objects with large effective radii. UDGs inside galaxy clusters have therefore very low internal accelerations which makes them ideal candidates for testing the MOND paradigm as a possible alternative to dark matter. Freundlich et al. (2022) studied the velocity dispersions of 11 UDGs in the Coma cluster and compared them with the predictions of MOND. The gravity from the cluster is expected to lower the internal gravitational accelerations of the UDGs due to the EFE, thus lowering their velocity dispersions, but the observed line-of-sight (l.o.s) velocity dispersions are higher than expected, and instead are actually in good agreement with the predictions of MOND in isolation, as if there was no EFE. The authors discussed several scenarios that could possibly explain this discrepancy:

1. The UDGs are undergoing their first infall onto the cluster and/or they are heated by tides.
2. They are surrounded by baryonic dark matter, such as moleculr hydrogen.
3. They have higher stellar masses than estimated from their photometry.
4. The MOND critical acceleration depends on the depth of the gravitational potential (the 'EMOND' hypothesis).
5. The MOND effects would depend on the trajectory of the system (modified inertia).
6. The EFE is screened in galaxy clusters within the parent modified gravity theory.
7. MOND is in fact an effective scaling relation emerging in the classical dark matter framework.

The first scenario can be tested using N-body simulations. Building on this work, we present here the results of numerical simulations of UDGs orbiting in the Coma cluster, in the MOND framework. We study their dynamical properties, compare them with observations, and subsequently try to assess whether these UDGs do pose a challenge to MOND or not.

2 Numerical methods

2.1 Coma cluster in MOND

From the X-ray emitting hot gas density, the cumulative mass profile is calculated assuming hydrostatic equilibrium and that the gas is isothermal. The Newtonian mass profile and the corresponding acceleration $a_C(R)$ are converted to MOND mass $M_C(R)$ using a simple interpolation function. All this is done in Eqs. 13 - 15 of Freundlich et al. (2022). The Newtonian mass profile is converted into a MOND mass profile using the simple interpolation function, We use the resulting cumulative mass profile, normalise it, and numerically invert the normalised function to generate a distribution function. We sample 10^5 particles of equal mass from this distribution and distribute them spherically symmetrically up to 5 Mpc from the center. These particles have masses of 4.18×10^9 $\mathrm{M}_\odot$ and are kept static during the simulation. Their purpose is to generate the potential of the Coma cluster through which the UDGs move.

2.2 UDGs in MOND

UDGs at the start of the simulations are approximated by Sérsic spheres with a mass of 10^7 $\mathrm{M}_\odot$, a Sérsic index 1.0 and an effective radius of 1.5 kpc. These parameters correspond to the medians of those indicated in Freundlich et al. (2022). A crucial aspect of our simulations was to ensure that the UDGs were in equilibrium given the EFE generated by the Coma cluster at their respective launch distances. This was achieved by using Eq. 25 of Freundlich et al. (2022), namely setting the internal accelerations of the UDGs after accounting for the EFE due to the Coma cluster.

Once the initial conditions for the cluster and the UDGs are set, we use the phantom of Ramses (POR; Lüghausen et al. 2015; Nagesh et al. (2021)) code to run the simulations. POR is a patch to the original RAMSES code (Teyssier (2002)) which implements a MOND Poisson solver alongside the already existing Newtonian one, thus enabling the users to run simulations in both Newtonian gravity and MOND. A user manual describing the procedure to setup, run, and analyse disc galaxies in MOND using POR is available online [*].

UDGs were launched into the Coma cluster at 1, 1.2, 1.4, 1.6, 1.8, 2.0 Mpc from the cluster center and, for each distance, with eccentricities of 0, 0.2, 0.4, 0.6, 0.8, and 0.99. In total, this results in 36 simulations which are run for 5 Gyr with outputs each 100 Myr.

3 Results

Particle data are extracted from the simulation outputs using EXTRACT_POR, barycentre subtracted, and analysed. In this on-going project, we have performed multiple analyses on the simulated UDGs, but we present here the most important one.

As mentioned in Section 1, a tension between the observed l.o.s. velocity dispersion and the MOND-predicted l.o.s. velocity dispersion was noted by Freundlich et al. (2022). We calculated the l.o.s. velocity dispersion, σ_{los}, in projection in the direction of the z axis/into the xy plane, for all simulated UDGs at the apocentre of their orbits and compared it with the MOND-predicted velocity dispersion in isolation, σ_{iso}. σ_{los} is calculated using Eq. 22 of Banik et al. (2020), and σ_{iso} is computed using methods described in Sec. 3.2.1 Freundlich et al. (2022). The latter estimates used Sérsic fit parameters obtained with GALFIT (Peng et al. 2010) at the corresponding times.

Fig. 1 shows the ratio $\sigma_{los}/\sigma_{iso}$ for the simulated UDGs at the apocentres of their orbits. These UDGs are launched at different distances from the cluster center and with different eccentricities. Dashed lines indicate that the UDGs are disrupted, which is defined as when they lose 80% of the mass within their initial tidal radius. The σ_{los} profiles of UDGs on orbits with $e < 0.6$ remain significantly below the isolated MOND limit. Although the UDG launched at 1 Mpc is disrupted due to tides, it still does not reach the isolated MOND limit. In contrast to the latter, quite a few UDGs on orbits with $e \geq 0.6$ reach the isolated MOND limit, but most of them are disrupted. The only UDG in our sample that has an inflated σ_{los} without being disrupted has an initial distance $R = 1.6$ Mpc and $e = 0.99$ (see bottom right plot). The shape of the σ_{los} profiles vary from $\sigma_{\rm los}$ declining with r to remaining flat to flaring up in the outskirts. An increase of σ_{los} towards the centre has been observed in the sample UDGs, and has been shown to be consistent with theoretical profiles including a radial anisotropy (for example, see Fig. 9 of Freundlich et al. (2022)). An increase in σ_{los} has also been observed in the profile of DF44 (van Dokkum et al. 2019; Freundlich et al. 2022).

4 Conclusions

Fig. 1 shows that UDGs need to be disrupted in order to have an inflated l.o.s. velocity dispersion, but the UDGs in the sample studied by Freundlich et al. (2022) have structural parameters like effective radius, and Sérsic index compatible with equilibrium. The analyses done so far thus indicate that it is quite difficult for the UDGs to survive a pericentric passage through the cluster and retain their structural properties whilst inflating their velocity dispersion to the isolated MOND prediction, which the observations seem to conform to. However, the detectability of the simulated UDGs still needs to be checked by constructing surface brightness maps and comparing them with observations. It is however important to note that the observations have large error bars and that the theoretical σ_{los} is within these error bars for some UDGs. Future observations could better constrain the σ_{los} values, which might increase or decrease the tension between theory and observations. With a few more tests, analyses, and simulations, we hope to conclude whether tidal disruption could possibly reconcile the observations with theoretical predictions or not.

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[*] `https://bitbucket.org/SrikanthTN/bonnPoR/src/master/`

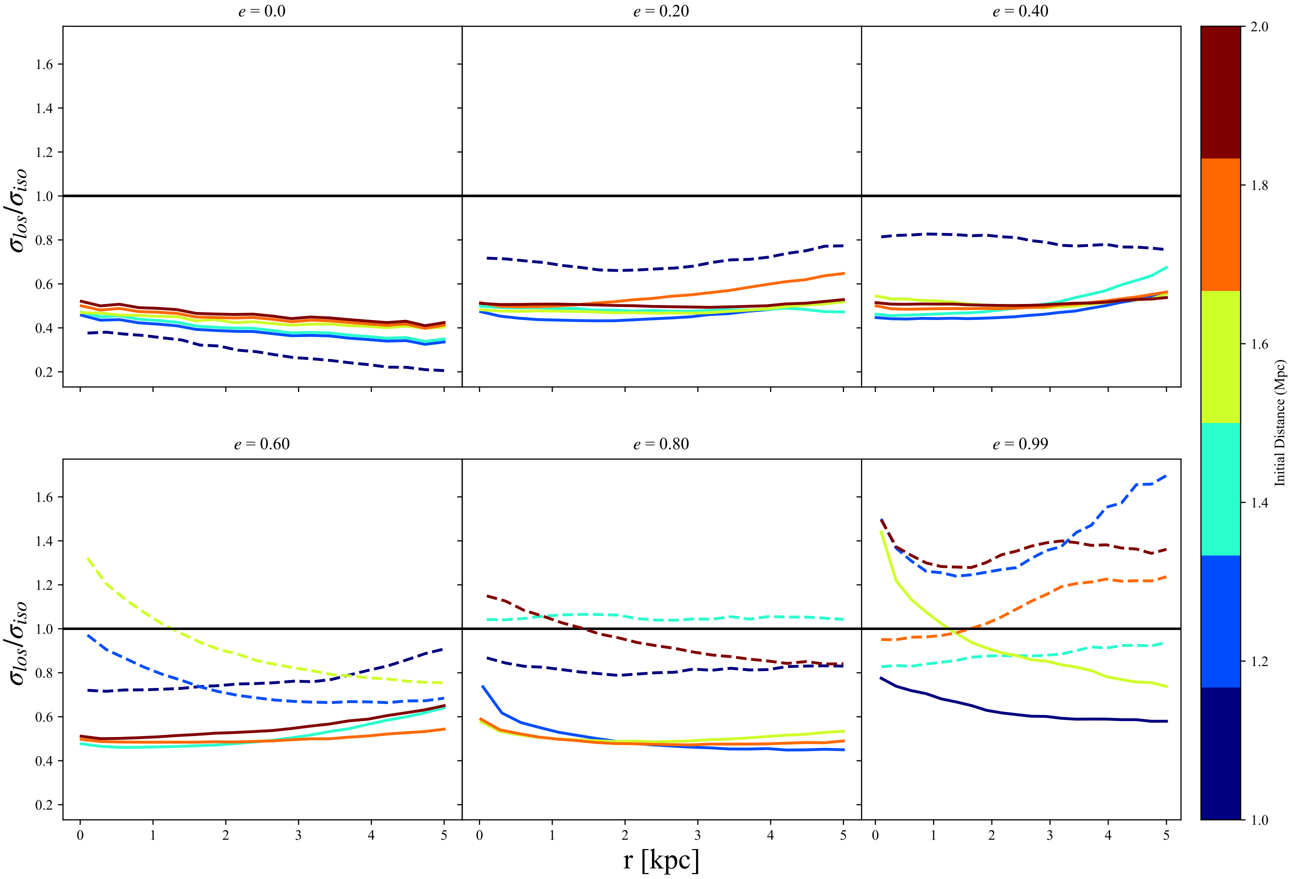

Fig. 1. Ratio between the simulated l.o.s. velocity dispersion, σ_{los}, and that predicted by MOND, σ_{iso}, for UDGs launched on orbits with different initial distances (cf. colorbar) and eccentricities ($e = 0, 0.2, 0.4, 0.6, 0.8, 0.99$). Dashed lines indicate that the UDG is disrupted or under disruption. The black solid line marks where $\sigma_{los} = \sigma_{iso}$.

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