THE MASS MISSING PROBLEM IN CLUSTERS: DARK MATTER OR MODIFIED DYNAMICS?

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The widely accepted dark matter hypothesis offers a seductive solution to missing mass problems (galaxies, clusters of galaxies, gravitational collapse in structure formation,...). However the physical nature of the Dark Matter itself is still unknown. Alternatively, it has been proposed that apparent dynamical evidence of dark matter is due to a modification of Newton’s law of gravitation. Here we revisit the Modified Newtonian Dynamics (MOND) theories at the scale of galaxy clusters. Using hydrodynamical simulations, we derived quantities such as the density and the temperature of the ICM. We compared those MOND simulated predictions to high quality X-ray density and temperature profiles observed down to $\sim 0.5$ the virial radius. If the density profiles seems in acceptable agreement, the simulated temperature show a constant increase with the radius whereas the observed profiles show a flat to a mild decrease shape down to $\sim 0.5 R_{\text{virial}}$. We also computed the dynamical MOND mass for 8 X-ray clusters observed with XMM-Newton. If the MOND mass helps to lower the discrepancy with the baryonic mass by $\sim 20\%$, still $\sim 80\%$ of the mass in clusters is unaccounted by baryons. In order to solve this problem and to reconcile MOND with clusters observations, we investigated the possibility of an added dark baryonic component. We assumed a component of massive neutrinos to fill the remaining discrepancy between the observed MOND dynamical mass and the baryonic mass. This led us to derive a tied observational lower limit for the neutrino mass, $m_\nu = 1.06$ eV.

1 Introduction

The missing mass problem in clusters of galaxies arises from the comparison of the observed baryonic mass with the observed dynamic mass. The baryonic mass is mainly due to the hot intracluster gas that is well observed in X-rays via its free-free emission. The current status of the observed gas fraction in clusters gives a fairly well constrained value of about 12% [see 10, 2, for instance]. Taking into account the stellar mass, this makes the discrepancy between the observed dynamic mass and the observed baryonic mass larger than a factor of 7.
We investigate in the following two hypothesis to solve this problem, the Dark Matter paradigm and the Modified Newtonian Dynamics paradigm.

2 The Dark side of the matter

The dark matter (DM hereafter) hypothesis appears to provide a seductive explanation of the mass missing problem. A new component of non-baryonic matter, insensitive to all interactions but gravitation, is introduced to fill the gap between the baryonic matter and the binding mass.

[16] have measured the total mass profile over a sample of ten clusters from 0.01 \( R_v \) up to 0.5 \( R_{200} \) using XMM-Newton observations. Their sample has an excellent temperature coverage and covers an order of magnitude in mass from \( M_v = 1.2 \times 10^{14} \ M_\odot \) to \( 1.2 \times 10^{15} \ M_\odot \).

They have found that the NFW profile is a good representation of the ten observed mass profiles, and that in all cases the isothermal sphere model (i.e a profile with a core) is rejected at high confidence. In other words, they confirm the cusped nature of the Dark Matter profile, as predicted by CDM simulations of hierarchical structure formation, over the temperature/mass range of the sample. The mass profile shape is close to universal, again as predicted, with a dispersion of less than 15% at 0.1 \( R_v \) in the scaled mass profiles. The shape is quantitatively consistent with theoretical predictions. The variation of the observed concentration parameters with mass is in line with the predictions, taking into account the measurement errors and the expected intrinsic scatter. Taken together, these results provide strong evidence in favour of the Cold Dark Matter cosmological scenario, and show that the physics of the Dark Matter collapse is well understood. The ten scaled profiles are presented on Fig. 1.

However, while cosmological evidence is accumulating in favour of this scenario (see for instance [7, 22, 23]), it is disconcerting that the nature of the non-baryonic dark matter is completely unknown. Of course there are many candidates of varying degrees of detectability and plausibility (e.g review by [4]).

3 Living in a MOND world

As an alternative to dark matter scenarios, [13] proposed a modification of the Newtonian dynamics effective at galactic and extra-galactic scales. This modified Newtonian dynamics
(MOND hereafter) has been notably successful in explaining the discrepancy between rotation and luminosity curves in spiral galaxies [11, 12], and claims other phenomenological successes (for a full review on MOND see [19]). The discrepancy between the baryonic mass and the dynamical mass in clusters of galaxies is perhaps foremost among the issues that MOND has yet to convincingly address.

The first confrontation of X-ray observations of clusters with MOND [9] emphasised the difficulties faced by MOND in passing the cluster test. The problem was revisited by [17, 18] and ended in a remaining discrepancy of a factor of 2-3 between the baryonic and the MOND masses. More recently, [1] discussed observational evidence for three clusters for which the observed discrepancy is about 1-5 within 1 Mpc and is boosted to a factor $\sim 10$ within the central 200 kpc, further weakening the reliability of the MOND paradigm. However, [20] responded with an update of his earlier work, introducing an added ad hoc dark component at the cluster centre to reduce the discrepancy to only a factor of 1-3 overall in the cluster.

Some other tests have also been carried out using gravitational lensing data. They have also pointed out the difficulties faced by MOND at the cluster scale [8, 5].

4 Revisiting MOND at galaxy clusters scale

Recently, [15] and [14] have revisited the MOND paradigm at the cluster scale. In the following we present a synthesis of their results.

4.1 Structure formation in MOND

[14] use a one dimensional hydrodynamical code to study the evolution of spherically symmetric perturbations in the framework of Modified Newtonian Dynamics (MOND). The code used evolves spherical gaseous shells in an expanding Universe by employing a MOND-type relationship between the fluctuations in the density field and the gravitational force, $g$. They focus on the evolution of initial density perturbations of the form $\delta_i \sim r_i^{-s}$ for $0 < s < 3$. A shell is initially cold and remains so until it encounters the shock formed by the earlier collapse of shells nearer to the centre. During the early epochs $g$ is sufficiently large and shells move according to Newtonian gravity. As the physical size of the perturbation increases with time, $g$ gets smaller and the evolution eventually becomes MOND dominated. However, the density in the inner collapsed regions is large enough that they re-enter the Newtonian regime. The evolved gas temperature and density profiles tend to a universal form that is independent of the the slope, $s$, and of the initial amplitude.

The results from the simulations, the temperature and density profiles of MOND, were confronted with recent X-ray observations of nearby galaxy clusters by XMM-Newton [16] and Chandra [24]. Among the different MOND runs, the minimum value number density at 500 kpc in MOND is $0.07 \, \text{cm}^{-3}$. This is substantially higher than the maximum observed number density of $0.0026 \, \text{cm}^{-3}$. More importantly, the temperature profile, $\sim r^{0.5}$ in MOND, is in clear contrast to the observed profiles, which either flatten or show a mild decline in the outer regions.

4.2 Observed clusters mass profiles versus MOND predictions

From the mass profiles derived by [16] in a LCDM cosmology, [15] computed the observed ratio of the dynamical MOND mass, $M_{m}$, to the baryonic mass $M_{b}$:

$$\frac{M_{m}(r)}{M_{b}(r)} = \left[ f_{gas}(1 + f_\star) \sqrt{1 + \left( \frac{a_0}{G M_{d}} \right)^2} \right]^{-1}$$

(1)
where $f_{\text{gas}}$ is the gas fraction, $f_*$ is the stellar fraction (i.e. the ratio of the stellar mass to the gas mass of the cluster). $a_0 \sim 10^{-8} \text{cm/s}^{-2}$ is a fundamental acceleration constant in the MOND theory (its value is derived from the analysis of the rotation curves of galaxies in a MOND framework), $G$ is the gravitational constant, $M_d$ is the hydrostatic mass of the cluster as obtained from the hydrostatic equilibrium equation.

In a pure MOND universe this ratio should equate 1. Table 1 reports the average baryon fraction values (i.e. $f_b = f_{\text{gas}} (1 + f_*)$) and the average $M_m/M_b$ ratios for the measured clusters at different radius. The computation were done at the following radii: the radii corresponding to the density contrasts, with respect to the critical density of the Universe at the cluster redshift of $\delta = 1000$ and $\delta = 15000$ (i.e $0.47 \pm 0.02 \ R_{200}$ and $0.10 \pm 0.01 \ R_{200}$ average over the eight out of ten clusters from [16]). Those two radii mark the boundaries of the radial range over which the observational constraints are especially well tied down.

At 0.5 $R_v$, the ratio of the MOND mass to the baryonic mass is $4.94 \pm 0.50$ ($10.6 \pm 3.77$ at

| Radius | $f_b$       | $M_m/M_b$    |
|--------|-------------|--------------|
| $\delta = 15000$ | $0.09 \pm 0.03$ | $10.6 \pm 3.77$ |
| $\delta = 1000$  | $0.13 \pm 0.02$  | $4.94 \pm 0.50$  |
This is more than a factor of two above the value derived by [18]. The evidence is confirmed if we only consider the hot systems. Indeed, for clusters with \(kT > 3.5\) keV, \(M_d/M_m = 1.43 \pm 0.08\) at \(\sim 0.5\) \(R_{200}\). This makes the ratio of the MOND mass to the baryonic mass \(\sim 5.10 \pm 0.56\). Thus in all cases, within a 3\(\sigma\) (i.e. 99% confidence) the ratio \(M_m/M_b\) in a MOND cosmology will be greater than 3.4, making MOND unable to fully overcome the missing mass problem in clusters. With respect to the used sample, in a MOND framework, still about 80\% of the total mass of galaxy clusters is missing at \(\sim 0.5\) \(R_{200}\). In other terms, this means that MOND just reduces the missing mass problem in clusters by about 20\% (at half the virial radius), but does not solve it.

4.3 Filling clusters with neutrinos

A last alternative to rescue MOND is to invoke a non-luminous component at the centre of clusters, as suggested recently by [20]. This author proposed massive neutrinos, aggregating at the cluster scale, as candidates for this dark component. More recently, [21] also called upon this neutrino hypothesis, studying formation of structures in the relativistic MOND framework (i.e. the Bekenstein theory [3]).

Further assuming a constant density sphere for this dark component and taking into account the phase space density limit for neutrinos, [20] derived an upper limit for the neutrino density after their collapse and accretion within structure of: \(\rho_{\nu} \leq (4.8 \times 10^{-24}) (m_{\nu}/2eV)^{1} (T_{\text{keV}})^{3/2} \text{kg/m}^{-3}\). We use the limit on the neutrino density, and we use the spectroscopic temperatures measured for each cluster of the previous sample between 0.1 and 0.5 \(R_{200}\) (see [16]). From the eight clusters, it is possible to compute the needed neutrino mass to equate the missing mass at a given radius (i.e. \(M_m(r) - M_b(r)\)) with the contribution of the massive neutrino to the cluster total mass. [20] hypothesis of the neutrino accretion mainly concerned the central parts of clusters. In our study, to explain the \(\sim 80\%\) of missing mass in MOND, we add to extend the radius of the neutrino sphere down to \(R_{1000}\). The minimum neutrino mass then required is \(m_{\nu} > 1.74 \pm 0.34\) eV. This is a strongly constraining value for the neutrino mass, which makes the lower bound for the neutrino mass becomes \(\sim 1.06\) eV, within a 2\(\sigma\) limit (i.e. 95\% confidence). This is barely compatible with the cosmological constraints from combined CMB+LSS data [22, 6].

5 Conclusion

We have presented here the case of two hypothesis to solve the missing mass problem at the galaxy clusters scale: The Dark Matter and the MOND paradigms. The Dark Matter hypothesis remains a very secure and stable grounds as it solve by definition the missing mass problem. However, the question of the nature of the Dark matter is still one of the most dazzling problem in modern astrophysics.

The MOND hypothesis, as a stand alone solution, has proven to be unable to solve the missing mass problem at the clusters scale. An added hot dark component is needed to rescue MOND, massive neutrinos for instance. As the amount of hot DM needed is up to \(\sim 80\%\) of the clusters mass, this turns the MONDian cosmological framework more into a mixed DM cosmology.

The results presented to this conference are extensively detailed the three following papers: Pointecouteau, Arnaud & Pratt (2005) [16], Pointecouteau & Silk (2005) [15] and Nusser & Pointecouteau (2006) [14].
References

[1] Aguirre A., Schaye J., Quataert E., 2001, ApJ, 561, 550
[2] Allen S. W., et al., 2003, MNRAS, 342, 287
[3] Bekenstein J. D., 2004, Phys. Rev. D, 70, 083509
[4] Bertone G., Hooper D., Silk J., 2004, Phys. Rep., 405, 279
[5] Clowe D., Gonzalez A., Markevitch M., 2004, ApJ, 604, 596
[6] Elgary ., Lahav O., 2005, New Journal of Physics, 7, 61
[7] Freedman W. L., et al., 2001, ApJ, 553, 47
[8] Gavazzi R., 2002, New Astronomy Review, 46, 783
[9] Gerbal D. et al., 1992, A&A, 262, 395
[10] Grego L., et al., 2001, ApJ, 552, 2
[11] Milgrom M., 1983a, ApJ, 270, 371
[12] Milgrom M., 1983b, ApJ, 270, 384
[13] Milgrom M., 1983c, ApJ, 270, 365
[14] Nusser, A., Pointecouteau, E. 2006, MNRAS, 366, 969
[15] Pointecouteau, E., Silk, J. 2005, MNRAS, 364, 654
[16] Pointecouteau, E., Arnaud, M., Pratt, G. W. 2005, A&A, 435, 1
[17] Sanders R. H., 1994, A&A, 284, L31
[18] Sanders R. H., 1999, ApJ, 512, L23
[19] Sanders R. H., McGaugh S. S., 2002, ARA&A, 40, 263
[20] Sanders R. H., 2003, MNRAS, 342, 901
[21] Skordis C., et al., 2006, Physical Review Letters, 96, 011301
[22] Spergel D. N., et al., 2003, ApJS, 148, 175
[23] Tegmark M., et al., 2004, Phys. Rev. D, 69, 103501
[24] Vikhlinin, A., et al., 2005, ApJ, 628, 655