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# Dark matter and modified Newtonian dynamics in a sample of high-redshift galaxy clusters observed with Chandra

Carl Blaksley [a,b], Massimiliano Bonamente [a,c,*]

[a] Department of Physics, University of Alabama, Huntsville, AL, USA
[b] Arnold Sommerfeld Center For Theoretical Physics, Faculty of Physics, Ludwig-Maximilians Universität, München, Germany
[c] NASA National Space and Science Technology Center, Huntsville, AL 35899, USA

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ABSTRACT

We compare the measurement of the gravitational mass of 38 high-redshift galaxy clusters observed by *Chandra* using Modified Newtonian Dynamics (MOND) and standard Newtonian gravity. Our analysis confirms earlier findings that MOND cannot explain the difference between the baryonic mass and the total mass inferred from the assumption of hydrostatic equilibrium. We also find that the baryon fraction at $r_{2500}$ using MOND is consistent with the Wilkinson Microwave Anisotropy Probe (WMAP) value of $\Omega_B/\Omega_M$.



## 1. Introduction

Since its introduction by Milgrom (1983), MOND had success in explaining galaxy rotation curves using only the mass-to-light ratio as a free parameter, and was able to predict the applicability of the Tully–Fisher relation to low surface brightness galaxies before dynamic information on them was available (Scarpa, 2006). These successes are not surprising, given the fact that MOND was created as a phenomenological theory in order to eliminate the need for dark matter in galaxies. Dark matter models are also very successful in describing the rotation curves of galaxies (e.g., Salucci and Persic, 1997; Persic et al., 1996).

While there have been numerous applications of MOND to individual galaxies, it is also important to study MOND on those scales where dark matter is believed to dominate, in particular that of galaxy clusters. There have been far fewer studies of MOND on this scale, with previous work on the subject including Sanders (1999), Aguirre et al. (2001), Pointecouteau and Silk (2005) and Angus et al. (2008). These results indicate that MOND does not eliminate the need for dark matter in galaxy clusters. In this paper we use MOND to calculate gravitational and baryonic masses for a sample of 38 galaxy clusters. The motivation of this work is the need to confirm the previous results by using a larger sample of massive clusters at high-redshift ($z = 0.14–0.89$).

We begin with a brief overview of the data and the models used, found in Section 2. Section 3 describes the calculation of the gas mass using X-ray observation, the derivation of the MOND acceleration, and the calculation of total masses from hydrostatic equilibrium. We then present our results in Section 4 and our conclusions in Section 5. The cosmological parameters $h = 0.7, \Omega_M = 0.3,$ and $\Omega_\Lambda = 0.7$ are used throughout this work.

## 2. Chandra X-ray data and data modeling

We analyze *Chandra* X-ray data from 38 clusters in the redshift range $z = 0.14–0.89$ (Table 1). The *Chandra* observations and the data modeling with the isothermal $\beta$ model are presented in Bonamente et al. (2006, 2008), LaRoque et al. (2006). Here we deal only with those aspects of the data modeling and analysis that are relevant to the present investigation.

The electron density model is based on the isothermal spherical $\beta$-model (Cavaliere and Fusco-Femiano, 1976, 1978), which has the form

$$n_e(r) = n_{e0}\left(1 + \frac{r^2}{r_c^2}\right)^{-3\beta/2}, \tag{1}$$

* Corresponding author.
*E-mail address:* bonamem@uah.edu (M. Bonamente).

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**Table 1**
Cluster parameters and masses for the isothermal $\beta$-model.

| Cluster | $z$ | $r_{2500}$ (arcsec) | $D_A$ (Gpc) | $M_{gas}$ $(10^{13}M_{\odot})$ | $M_{total}$ $(10^{14}M_{\odot})$ | $M_{Mond}$ $(10^{14}M_{\odot})$ |
|---|---|---|---|---|---|---|
| Abell1413 | 0.143 | $201.6^{+5.2}_{-4.6}$ | 0.52 | $2.63^{+0.11}_{-0.1}$ | $2.15^{+0.17}_{-0.14}$ | $1.51^{+0.14}_{-0.12}$ |
| Abell1689 | 0.18 | $217.1^{+5.1}_{-5.5}$ | 0.63 | $5.1^{+0.17}_{-0.17}$ | $4.95^{+0.36}_{-0.36}$ | $3.97^{+0.32}_{-0.33}$ |
| Abell1835 | 0.25 | $171.1^{+5}_{-4.4}$ | 0.81 | $5.81^{+0.23}_{-0.2}$ | $5.55^{+0.5}_{-0.42}$ | $4.59^{+0.46}_{-0.38}$ |
| Abell1914 | 0.17 | $226.7^{+4.6}_{-4}$ | 0.6 | $4.87^{+0.12}_{-0.1}$ | $4.82^{+0.3}_{-0.25}$ | $3.85^{+0.27}_{-0.22}$ |
| Abell1995 | 0.32 | $133.4^{+4.5}_{-4.7}$ | 0.96 | $3.51^{+0.14}_{-0.14}$ | $4.74^{+0.5}_{-0.48}$ | $3.91^{+0.46}_{-0.44}$ |
| Abell2111 | 0.23 | $140.5^{+9.8}_{-8.9}$ | 0.76 | $2.19^{+0.27}_{-0.23}$ | $2.49^{+0.56}_{-0.44}$ | $1.84^{+0.48}_{-0.37}$ |
| Abell2163 | 0.2 | $206.7^{+3}_{-2.9}$ | 0.68 | $8.08^{+0.21}_{-0.2}$ | $5.49^{+0.24}_{-0.23}$ | $4.47^{+0.22}_{-0.21}$ |
| Abell2204 | 0.15 | $256.1^{+13}_{-11}$ | 0.54 | $4.74^{+0.27}_{-0.24}$ | $4.96^{+0.8}_{-0.64}$ | $3.95^{+0.72}_{-0.57}$ |
| Abell2218 | 0.18 | $190^{+5.7}_{-5.4}$ | 0.63 | $3.02^{+0.13}_{-0.12}$ | $3.32^{+0.31}_{-0.27}$ | $2.53^{+0.27}_{-0.24}$ |
| Abell2259 | 0.16 | $172.1^{+8.3}_{-7.9}$ | 0.57 | $1.82^{+0.14}_{-0.14}$ | $1.79^{+0.27}_{-0.24}$ | $1.23^{+0.22}_{-0.19}$ |
| Abell2261 | 0.22 | $148.3^{+6.7}_{-6.3}$ | 0.73 | $3.03^{+0.2}_{-0.19}$ | $2.56^{+0.36}_{-0.31}$ | $1.9^{+0.31}_{-0.26}$ |
| Abell267 | 0.23 | $131.3^{+8.5}_{-7.5}$ | 0.76 | $2.24^{+0.2}_{-0.18}$ | $2.03^{+0.42}_{-0.33}$ | $1.46^{+0.35}_{-0.27}$ |
| Abell370 | 0.38 | $97.95^{+4.1}_{-4.1}$ | 1.07 | $2.78^{+0.21}_{-0.2}$ | $2.78^{+0.37}_{-0.33}$ | $2.19^{+0.33}_{-0.29}$ |
| Abell586 | 0.17 | $181.6^{+8}_{-7}$ | 0.6 | $2.27^{+0.13}_{-0.11}$ | $2.48^{+0.34}_{-0.28}$ | $1.8^{+0.29}_{-0.23}$ |
| Abell611 | 0.29 | $110.3^{+3.6}_{-3.5}$ | 0.9 | $2.37^{+0.11}_{-0.11}$ | $2.13^{+0.22}_{-0.2}$ | $1.58^{+0.19}_{-0.17}$ |
| Abell665 | 0.18 | $160.5^{+3.6}_{-3.3}$ | 0.63 | $2.63^{+0.1}_{-0.095}$ | $2^{+0.14}_{-0.12}$ | $1.41^{+0.11}_{-0.099}$ |
| Abell68 | 0.26 | $153^{+10}_{-9.3}$ | 0.83 | $3.65^{+0.34}_{-0.31}$ | $4.32^{+0.91}_{-0.74}$ | $3.48^{+0.82}_{-0.66}$ |
| Abell697 | 0.28 | $133.1^{+5}_{-4.9}$ | 0.88 | $4.4^{+0.28}_{-0.26}$ | $3.46^{+0.4}_{-0.37}$ | $2.73^{+0.36}_{-0.32}$ |
| Abell773 | 0.22 | $148.9^{+5.6}_{-5.3}$ | 0.73 | $2.74^{+0.17}_{-0.15}$ | $2.59^{+0.3}_{-0.27}$ | $1.93^{+0.26}_{-0.23}$ |
| CLJ0016 + 1609 | 0.54 | $79.85^{+3}_{-3}$ | 1.31 | $4.38^{+0.29}_{-0.29}$ | $3.33^{+0.39}_{-0.37}$ | $2.8^{+0.36}_{-0.34}$ |
| CLJ1226 + 3332 | 0.89 | $66.02^{+7.4}_{-6.5}$ | 1.6 | $3.89^{+0.51}_{-0.46}$ | $5.21^{+2}_{-1.4}$ | $4.8^{+1.9}_{-1.3}$ |
| MACSJ0647.7 + 7015 | 0.58 | $91.94^{+6.2}_{-5.7}$ | 1.36 | $4.91^{+0.47}_{-0.42}$ | $5.97^{+1.3}_{-1.1}$ | $5.31^{+1.2}_{-1}$ |
| MACSJ0744.8 + 3927 | 0.69 | $58.88^{+3.5}_{-3.2}$ | 1.47 | $3.08^{+0.27}_{-0.25}$ | $2.26^{+0.42}_{-0.35}$ | $1.89^{+0.39}_{-0.32}$ |
| MACSJ1149.5 + 2223 | 0.54 | $70.64^{+3.9}_{-3.6}$ | 1.31 | $3.09^{+0.34}_{-0.3}$ | $2.31^{+0.4}_{-0.34}$ | $1.86^{+0.37}_{-0.3}$ |
| MACSJ1311.0 − 0310 | 0.49 | $73.92^{+7.6}_{-6.6}$ | 1.25 | $2.12^{+0.25}_{-0.21}$ | $2.17^{+0.74}_{-0.53}$ | $1.71^{+0.66}_{-0.47}$ |
| MACSJ1423.8 + 2404 | 0.55 | $65.93^{+2.1}_{-2}$ | 1.32 | $2.26^{+0.1}_{-0.096}$ | $1.94^{+0.2}_{-0.18}$ | $1.54^{+0.17}_{-0.16}$ |
| MACSJ2129.4 − 0741 | 0.57 | $72.42^{+4.6}_{-4.1}$ | 1.35 | $3.27^{+0.3}_{-0.26}$ | $2.82^{+0.57}_{-0.45}$ | $2.35^{+0.53}_{-0.41}$ |
| MACSJ2214.9 − 1359 | 0.482 | $91.31^{+5.1}_{-4.9}$ | 1.23 | $3.94^{+0.32}_{-0.31}$ | $3.85^{+0.68}_{-0.59}$ | $3.24^{+0.63}_{-0.54}$ |
| MACSJ2228.5 + 2036 | 0.41 | $83.61^{+4.1}_{-3.8}$ | 1.12 | $2.78^{+0.23}_{-0.21}$ | $2.05^{+0.32}_{-0.27}$ | $1.57^{+0.28}_{-0.23}$ |
| MS0451.6 − 0305 | 0.55 | $82.18^{+3.7}_{-3.5}$ | 1.32 | $4.8^{+0.32}_{-0.3}$ | $3.76^{+0.53}_{-0.46}$ | $3.2^{+0.49}_{-0.43}$ |
| MS1054.5 − 0321 | 0.83 | $33.74^{+7.1}_{-8.5}$ | 1.57 | $0.905^{+0.55}_{-0.49}$ | $0.612^{+0.47}_{-0.36}$ | $0.454^{+0.41}_{-0.29}$ |
| MS1137.5 + 6625 | 0.78 | $41.63^{+3.3}_{-2.9}$ | 1.54 | $1.26^{+0.15}_{-0.14}$ | $1.02^{+0.26}_{-0.2}$ | $0.802^{+0.23}_{-0.18}$ |
| MS1358.4 + 6245 | 0.33 | $113.4^{+5.8}_{-5.2}$ | 0.98 | $2.53^{+0.19}_{-0.17}$ | $3.13^{+0.51}_{-0.41}$ | $2.47^{+0.45}_{-0.36}$ |
| MS2053.7 − 0449 | 0.58 | $54.2^{+5.1}_{-4.6}$ | 1.36 | $0.933^{+0.13}_{-0.12}$ | $1.22^{+0.38}_{-0.29}$ | $0.921^{+0.33}_{-0.24}$ |
| RXJ1347.5 − 1145 | 0.45 | $122.3^{+3.8}_{-3.6}$ | 1.19 | $8.86^{+0.37}_{-0.35}$ | $8.08^{+0.77}_{-0.69}$ | $7.18^{+0.73}_{-0.65}$ |
| RXJ1716.4 + 6708 | 0.81 | $45.01^{+4.4}_{-3.9}$ | 1.56 | $1.23^{+0.19}_{-0.16}$ | $1.39^{+0.45}_{-0.33}$ | $1.14^{+0.41}_{-0.3}$ |
| RXJ2129.7 + 0005 | 0.24 | $128.5^{+5.3}_{-4.9}$ | 0.78 | $2.57^{+0.16}_{-0.14}$ | $2.08^{+0.27}_{-0.23}$ | $1.5^{+0.22}_{-0.19}$ |
| ZW3146 | 0.29 | $131.5^{+2.6}_{-2.5}$ | 0.9 | $4.44^{+0.11}_{-0.11}$ | $3.62^{+0.22}_{-0.2}$ | $2.87^{+0.19}_{-0.18}$ |

where $n_{e0}$ is the central electron number density, $r_c$ is a core radius, and $\beta$ is a power-law index. The radial profile of the X-ray surface brightness is obtained via integration along the line of sight, and results in the following analytical expression:

$$S_x = S_{x0}\left(1+\frac{\theta^2}{\theta_c^2}\right)^{(1-6\beta)/2}. \tag{2}$$

Best-fit model parameters and confidence intervals for all model parameters are obtained using a Markov chain Monte Carlo (MCMC) method described in detail by Bonamente et al. (2004) and LaRoque et al. (2006). For each cluster, the Markov chain constrains the parameters $S_{x0}, \beta, \theta_c, T_e$, and the chemical abundance (see LaRoque et al. (2006) for best-fit values). We use the cosmological parameters $h = 0.7, \Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ to calculate each cluster's angular diameter distance $D_A$ (e.g., Carroll et al., 1992).

All of our calculations are done out to a maximum radius of $r_{2500}$, the radius at which the cluster mass density is 2500 times the critical density, which is also approximately the radius out to which our *Chandra* data are sensitive without any extrapolation of the models. In LaRoque et al. (2006) we have compared masses obtained using the simple isothermal $\beta$ model with those obtained using a more complex non-isothermal $\beta$ model, and shown that the two methods yield the same ratio of baryonic to total mass. The non-isothermal model included a double $\beta$ model distribution for the density (Eq. (7) in LaRoque et al., 2006), and an arbitrary temperature profile that was constrained by assuming that the plasma is in hydrostatic equilibrium with an NFW potential (Eq. (8) in LaRoque et al., 2006). We therefore, expect no significant bias in the study of MOND masses using this simple model, which has the advantage of analytical expressions for the observables and the masses.

## 3. Calculation of gas, Newtonian and MOND masses

For the isothermal $\beta$ model, the gas mass enclosed within a given cluster radius is given by (e.g. LaRoque et al., 2006)

$$M_{gas}(r) = A\int_0^{r/D_A}\left(1+\frac{\theta^2}{\theta_c^2}\right)^{-3\beta/2}\theta^2\,d\theta, \tag{3}$$

where $A = 4\pi\mu_e n_{e_0} m_p D_A^3$, $\mu_e$ is the mean electron weight (calculated from the *Chandra* data, with typical value of $\mu_e = 1.17$), and $D_A$ is the cluster distance. The central electron density $n_{e_0}$ is