Radial acceleration relation of elliptical galaxies in MaNGA

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Abstract

The relationship between the total and baryonic acceleration of a galaxy is the Radial Acceleration Relation (RAR). Data of 88 elliptical galaxies were selected from Sloan Digital Sky Survey Data Release 18 (SDSS DR18), and the $M_{\rm gas}$ of each are specifically taken from the Mapping of Nearby Galaxies at Apache Point Observatory (MaNGA) data set. Hernquist model is used for the baryonic component of the ellipticals, as well as for the dark matter halo and in Modified Newtonian Dynamics (MOND). The RAR results of the samples are separated into high and low mass galaxies, and their $M_{\rm dyn}$–$M_{\rm bar}$ relationship are compared. A value for the MOND acceleration constant a_0 averaged across all 88 elliptical galaxies is found to be within $(1.648 - 3.501) \times 10^{-10}\,{\rm m/s^2}$ when gas mass is considered.

Keywords: MOND, mass discrepancy, galaxy, dark matter, cosmology

1 Introduction

The missing mass problem in galaxies presents a long-standing challenge for conventional physical theories employing Newtonian mechanics [1–4]. Mass discrepancy is simply the inequality of a galaxy's luminous mass against its observed dynamics; and the missing mass is attributed to dark matter in literature. This kind of exotic matter is believed to be the cause of unusual galaxy rotation, galaxy evolution, and large scale structure formation.

Modified Newtonian dynamics (MOND) offers an alternative to dark matter to account for the missing mass. Proposed by Milgrom (1983) [5], and McGaugh et al. (2016) [6] later supported MOND's case through the Radial Acceleration Relation (RAR) of galaxies. Note that spiral galaxies are predominantly the subjects of RAR measurements in literature, while few are dedicated to elliptical galaxies – which are pressure-supported systems and model dependent. It is important to study the RAR of galaxies to determine if there is a one constant acceleration scale that is present in all kinds of galaxies which serves as the transition towards the MOND regime. These discrepancies are studied as it also hints on the possibility of new particles in the Standard Model of Particle Physics [7], or the need of modifications in our currently accepted laws and theories regarding galactic and extra-galactic dynamics. However, most of the studies on RAR have been conducted on spiral galaxies due to their simple dynamics. This limits our understanding on the missing mass problem in elliptical galaxies, and it is in this light that this study was conducted [8].

In this paper, the RAR and the effect of gas mass on elliptical galaxies from the Sloan Digital Sky Survey Data Release 18 (SDSS DR18) are explored.

2 Methodology and Results

2.1 Data Selection

Data of 88 elliptical galaxies were selected from the *Galaxy* table of SDSS-DR18, and using selection criteria from Galaxy Zoo [9] and the NASA-Sloan Atlas (NSA) Catalog [10], stellar mass and velocity dispersion data from Chen et al. (2011) [11], and gas mass data are finally added from MaNGA [12]. Additionally, this work uses a flat ΛCDM model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and a Hubble Constant of $H_0 = 70\ {}^{km}/_{s \cdot Mpc}$. The summary of the criteria are tabulated in Table 1. Note that there is no mass cutoff applied to the sample selection, so there are some that could be considered dwarf galaxies – but they too exhibit dynamic masses ($M_{\rm dyn} = M_{DM} + M_{\rm bar}$) far greater than their baryonic mass [13–15].

2.2 MOND/DM Model, and Other Equations

Different models are used to analyze the extent of the mass (or acceleration) discrepancies of each elliptical galaxy. Specifically for the baryonic mass distribution and dark matter halo respectively, the Hernquist model [16] and Singular Isothermal Sphere (SIS) are used for their simplicity, while other models from literature are included for comparison.

To derive the acceleration due to gravity g_{tot} (or $\nabla\Phi$ from Gauss's law of gravity) through different interpolating functions (IF) in MOND, the equation

$$\mu(x) g_{tot} = g_{\rm bar}, \quad x = \frac{|g_{tot}|}{a_0} \tag{1}$$

is used where $\mu(x) \rightarrow 1$ when $x \rightarrow \infty$, and $\mu(x) \rightarrow x$ when $x \rightarrow 0$. Note that in the context of gravity, a and g are interchangeable depending on the assignment or usage. If Equation (1) is inverted, we get the ν-form IF

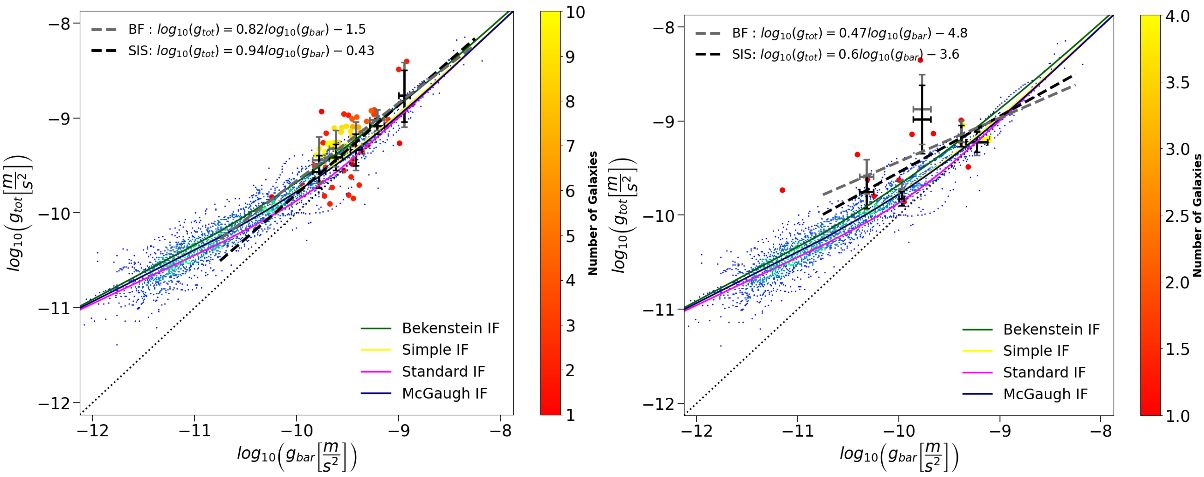
$$g_{tot} = \nu(x_N) g_{\rm bar}, \quad x_N = \frac{|g_{\rm bar}|}{a_0}, \tag{2}$$

where $\nu(x_N) \rightarrow 1$ when $x_N \rightarrow \infty$ and $\nu(x_N) \rightarrow \dfrac{1}{\sqrt{x_N}}$ when $x_N \rightarrow 0$.

The models from literature used for comparison in this work, all under the MOND paradigm, are the simple, standard, and Bekenstein forms [17–20].

An isotropic velocity dispersion via Jeans equation was assumed, and Hernquist Model, SIS, and Bekenstein Form (BF) were all used to derive the cumulative surface brightness weighted velocity dispersion – which is used because the selected samples only have one point of velocity dispersion data, unlike the typical samples of spiral galaxies which have multiple observed points. Refer to Sace & Ko (2021) [8] for more an in-depth discussion regarding the models and equations.

For the line fitting, Least Square (LSQ) method was used (see Figures 1), which basically assumes that the relationship between the y and x data follows a first-degree polynomial $y = Ax + B$ (slope-intercept form) where $y = \log_{10} g_{tot}$ and $x = \log_{10} g_{\rm bar}$.



71 High Mass Ellipticals

17 Low Mass Ellipticals

Figure 1: The RARs of the 88 SDSS-DR18 elliptical galaxies separated into 71 high mass ($M_* > 10^{10.4} M_\odot$) and 17 low mass ($M_* < 10^{10.4} M_\odot$) elliptical galaxies respectively, represented by the red color mapped dots. The blue color mapped dots represent the 2693 spiral galaxy samples of McGaugh et al. (2016) [6]. The x-axis is the baryonic acceleration, and the y-axis is the total acceleration. The black and gray error bars represent SIS and BF fitting. The green, yellow, magenta, and blue lines correspond to the Bekenstein, simple, standard, and McGaugh IFs from literature. The binning was done within the minimum and maximum values of $g_{\rm bar}$, and an outlier was removed due to high spread which makes the data set not follow the empirical rule.

2.3 RAR of the Samples

The resulting RARs of the samples separated into high mass ($M_* > 10^{10.4} M_\odot$) and low mass ($M_* < 10^{10.4} M_\odot$) galaxies are shown in Figure 1. Based on the results, high mass galaxies seem to tend towards

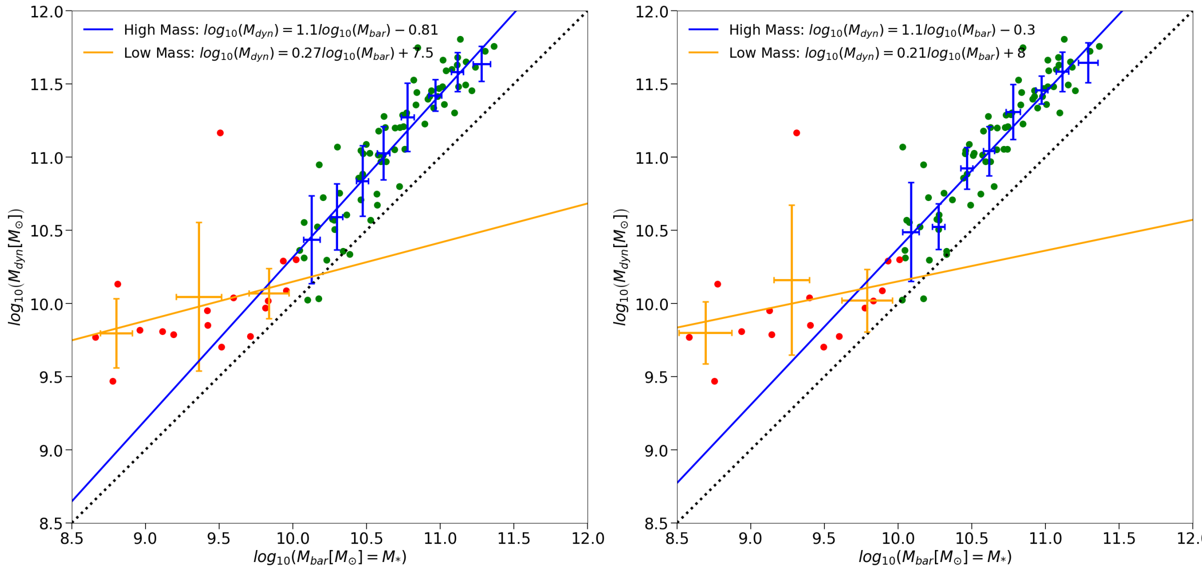
Table 1: Selection criteria used for getting the 88 elliptical galaxies from SDSS-DR18 + MaNGA.

fracDev	Sérsic index	Absolute Magnitude	Axis Ratio
> 0.8	$3 < n < 6$	$M_r < -23$	> 0.80
Morphology from Galaxy Zoo: debiased spiral votes < 0.3, debiased elliptical votes > 0.7			

the Newtonian regime with a slope closer to 1, while the low mass galaxies seem to tend towards the MOND regime with a slope closer to 0.5 – which are generally accepted slopes [5, 6, 21]. However, at lower acceleration, it diverges away from IFs found in literature. This implies that there are more non-baryonic matter in low mass galaxies that remain undetected.

Additionally, the relationship of the inferred dynamic mass and the baryonic mass M_{bar} of the galaxy samples are shown in Figure 2. The difference between the trend of the high mass and low mass galaxies is apparent, where the high mass galaxies' M_{dyn}–M_{bar} relationship is closer to the unity line, while the low mass galaxies have a flatter relationship. Both sets of galaxies slightly moved closer to the unity line with the inclusion of gas mass, but the low mass galaxies had a slightly steeper slope.

Lastly, the ellipticals seem to generally lie on the Newtonian regime compared to the spirals which extend to the deep MOND regime, and this may be due to the lack of multiple data points of velocity dispersions, different dynamics, or limitations of the SDSS data set.



With gas — No gas

Figure 2: The relationship of the M_{dyn}(y-axis) and M_{bar}(x-axis) of the samples with (left) and without (right) gas mass. The red and green dots are the low and high mass galaxies respectively, while the orange and blue lines are the LSQ fittings for each respectively. The same binning procedure from Figure 1 are also used here.

All the calculated numerical results are summarized in Table 2, where mean mass ratio, the Mean Absolute Deviation (MAD) of the M_{dyn} and M_{bar}, mean a_0 value, and the RAR LSQ fitting are included.

Table 2: Summary of the calculated numerical results.

Data set	**Mean** $\frac{M_{\text{dyn}}}{M_{\text{bar}}}$	**MAD:**		**Mean** $\frac{a_0}{g_\dagger}$	**LSQ:** $y =$	
		M_{dyn}	M_{bar}		BF	SIS
Low mass (17)	7.104	0.367	0.288	12.20	$0.47x - 4.8$	$0.60x - 0.36$
High Mass (71)	2.808	0.242	0.359	2.199	$0.82x - 1.5$	$0.94x - 0.43$

3 Conclusions

Based on the RAR in Figure 1, there is an apparent difference between the dynamic behaviors of high mass and low mass elliptical galaxies, and the M_{dyn}–M_{bar} relation in Figure 2 also seem to indicate that low mass galaxies have a more massive dark matter halo compared to high mass galaxies. Adding a galaxy's gas mass as an additional component of a galaxy's baryonic mass reduces the discrepancy of dark matter mass and luminous mass – thus the calculated acceleration scale a_0 for the 88 elliptical galaxies analyzed in this study is closer to $g_\dagger = 1.20 \pm 0.02$ (random) ± 0.24 (systematic) $\times 10^{-10}\ {}^{m}/_{s^2}$ [6], but more samples in the MOND regime are needed to draw something conclusive. Lastly, a_0 value for all the ellipticals is calculated to be within $(1.648 - 3.501) \times 10^{-10}\,{}^{m}/_{s^2}$, where 1.648 is the best fit value and 3.501 is the average for all 88 ellipticals.

More data and analysis will be further conducted in the future, such as adding galaxies with multiple velocity dispersion points, or making a comparison of the RAR of dwarf galaxies and low surface brightness elliptical galaxies compared to high mass galaxies – which will be this work's next focus.

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