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Extending the Radial Acceleration Relation using Weak Gravitational Lensing with the Kilo-Degree Survey

Margot M. Brouwer[1,2]*,

[1] *Kapteyn Astronomical Institute, University of Groningen, PO Box 800, NL-9700 AV Groningen, the Netherlands.*
[2] *Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands.*

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ABSTRACT
TBW

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* E-mail:brouwer@astro.rug.nl

1 INTRODUCTION

It has been known for several decades that the outer regions of galaxies rotate faster than would be expected from Newtonian dynamics, based on their luminous (baryonic) mass. This was first discovered by Rubin (1983) through measuring galactic rotation curves of optical disks, and by Bosma (1981) through measuring hydrogen profiles at radii beyond the disk. The excess gravity implied by these measurements have been generally attributed to an unknown and invisible substance named Dark Matter (DM), a term coined earlier by Zwicky (1937) when he discovered the missing mass problem through the dynamics of galaxies in clusters.

Following more recent observations using Weak gravitational Lensing (WL, Hoekstra et al. 2004; von der Linden et al. 2014; Mandelbaum 2015), Baryon Acoustic Oscillations (BAO's, Eisenstein et al. 2005; Blake et al. 2011) and the Cosmic Microwave background (CMB, Spergel et al. 2003; Planck XIII 2016), cold dark matter[1] (CDM) became a key ingredient of the current standard model of cosmology: the ΛCDM model. In this paradigm, CDM accounts for $\Omega_{\rm CDM} = 0.266$ of the critical density in the Universe, while the cosmological constant Λ necessary to explain the accelerated expansion of the Universe (which is usually associated with dark energy; DE) accounts for $\Omega_\Lambda = 0.685$.

Although the ΛCDM model successfully describes the behavior of DM on a wide range of scales, no conclusive evidence for the existence of DM particles has been found so far (despite years of enormous effort; for an overview, see Bertone et al. 2005; Bertone & Tait 2018). This still leaves some room for alternative theories of gravity, such as Modified Newtonian Dynamics (MOND, Milgrom 1983) and the more recent theory of Emergent Gravity (EG, Verlinde 2016). In these theories DM does not exist, and all gravity is due to the baryonic matter (or, in the case of EG, the interaction between baryons and the entropy associated with DE). Hence, one of the main properties of these theories is that the mass discrepancy in galaxies correlates strongly with their baryonic mass distribution.

Such a correlation has indeed been widely observed. First astronomers discovered the Tully-Fisher relation (TFR, Tully & Fisher 1977) between the luminosity of a spiral galaxy and its asymptotic rotation velocity (Pierce & Tully 1988; Bernstein et al. 1994). Since this corresponds to a relation between the baryonic and the total galaxy mass, this has later been named the 'baryonic' TFR (BTFR, McGaugh et al. 2000; McGaugh 2012). As the radial resolution of observations increased, astronomers found a strong correlation between the observed rotation velocity $v_{\rm obs}(r)$ as a function of galaxy radius r, and the enclosed luminous mass $m_{\rm bar}(<r)$ (Sanders 1986, 1996; McGaugh 2004; Sanders & Noordermeer 2007; Wu & Kroupa 2015). Since $m_{\rm bar}(<r)$ corresponds to the *expected* gravitational acceleration $g_{\rm bar}(r)$ from baryonic matter, and the observed gravitational acceleration can be calculated through $g_{\rm obs}(r) = v^2_{\rm obs}(r)/r$, this relation has been named the Radial Acceleration Relation (RAR)[2].

Particularly, the latest results from McGaugh et al. (2016) (hereafter M16) have measured the RAR relation with unprecedented accuracy, using the Spitzer Photometry and Accurate Rotation Curves (SPARC, Lelli et al. 2016) data of 153 late-type galaxies. Their results showed a tight correlation between $g_{\rm obs}$ and $g_{\rm bar}$, which they could fit using a simple double power law (Eq. 4 in M16) depending only on $g_{\rm bar}$ and one free parameter: the acceleration scale $g_\dagger$ where Newtonian gravity appears to break down. This sparked the interest of scientists working on alternative theories of gravity, but also of those in favor of a statistical explanation of the RAR within the ΛCDM framework (Keller & Wadsley 2017; Desmond 2017; Ludlow et al. 2017).

The latter possibility was quantified by Navarro et al. (2017) (hereafter N17) who used a range of simplifying assumptions based on galaxy observations and DM simulations, in order to create an analytical galaxy+halo model. The goal of their model was to reconstruct the RAR in galaxies, in particular the value of a_0: the acceleration scale where the relation transitions from the baryon-dominated to the DM-dominated regime (which is equivalent to $g_\dagger$), and $a_{\rm min}$: the minimum acceleration probed by galaxy disks. Based on their results, they claimed that the RAR can be explained within the ΛCDM framework, at the accelerations probed by galaxy rotation curves (i.e. $g_{\rm obs} > a_{\rm min}$). However, since their model relies on the fact that luminous kinematic tracers in galaxies only probe a limited radial range, N17 predicted that extending observations to radii beyond the disk (which correspond to lower gravitational accelerations) would lead to systematic deviations from the simple relation posed by M16.

The goal of this work is to extend observations of the RAR to lower accelerations, which are not measurable using galaxy rotation curves. To this end we use gravitational lensing: the perturbation of light inside a gravitational potential as described by General Relativity (GR). In particular, we use the method of Galaxy-Galaxy Lensing (GGL): the statistical measurement of the coherent image distortion (shear) of a field of background galaxies (sources) by the gravitational potential of a sample of foreground galaxies (lenses) (for examples, see e.g. Fischer et al. 2000; Hoekstra et al. 2004; Mandelbaum et al. 2006; van Uitert et al. 2016). Using GGL we can measure the average (apparent) density distribution of galaxies up to a radius of 3 Mpc, roughly a 100 times larger than the radius of the luminous disk (~ 30 kpc), corresponding to a value of $g_{\rm bar}$ that is roughly 3 orders of magnitude lower than those measurable with galaxy rotation curves.

First, we measure the baryonic and total density profiles of our galaxies through their luminosities and GGL profiles. These measurements will be performed using photometric data from Sloan Digital Sky Survey (Abazajian et al. 2009, SDSS,) and the VISTA Kilo-Degree Infrared Galaxy survey (Edge et al. 2013, VIKING), and weak lensing data from the Kilo-Degree Survey (KiDS, de Jong et al. 2017). We then translate these measurements into the baryonic and

[1] DM particles that moved at non-relativistic speeds at the time of recombination, as favoured by measurements of the CBM (Planck XVI 2014) and the Lyman-α forest (Viel et al. 2013).
[2] Another well-established name for this same relation is the Mass-Discrepency Acceleration Relation (MDAR), which refers to the correspondance between the observed baryonic/total mass and the inferred mass discrepency commonly attributed to DM. Throughout this work we use the term RAR for brevity.

observed radial accelerations, $g_{\rm bar}$ and $g_{\rm obs}$. Finally, we compare the resulting RAR to predictions from different modified gravity theories (MOND and EG) and ΛCDM.

The ΛCDM predictions will not only be provided by the N17 analytical model, but also by two mock galaxy catalogues based on two different DM simulations. One is the Marenostrum Institut de Ciències de l'Espai (MICE) Galaxy and Halo Light-cone catalog (Carretero et al. 2015; Hoffmann et al. 2015), which is based on the MICE Grand Challenge lightcone simulation (MICE-GC, Fosalba et al. 2015a,b; Crocce et al. 2015). The other mock galaxy catalog is based on a suite of large-volume cosmological hydrodynamical simulations, which is called the BAryons and HAloes of MAssive Systems (BAHAMAS) project (McCarthy et al. 2017). Our final goal is to distinguish which of the aforementioned predictions best describe the RAR at lower accelerations.

Having over ... foreground galaxies at our disposal, we are able to select specific lens samples designed to optimally test these predictions. Particularly, we note that most models (MOND, EG, and the N17 analytical DM model) focus on the description of individual, isolated galaxies. In order to test them, therefore, we select a sample of galaxies whose lensing profiles are not affected by their neighbors within the radius of our measurement. In contrast, the predictions from the MICE and BAHAMAS simulations can be tested for both isolated and non-isolated galaxy samples.

Furthermore, we note that all models give a specific prediction regarding the dependence of the RAR on baryonic galaxy mass. According to the MOND and EG theories, the relation between $g_{\rm bar}$ and $g_{\rm obs}$ should remain intact in the regime beyond the disk, independent of the disk mass. Within the ΛCDM paradigm, however, all predictions (analytical and simulated) are based on a 'stellar-to-halo-mass relation' which is not constant as a function of baryonic galaxy mass. By splitting our foreground galaxies into bins of increasing stellar mass, we are able to better distinguish the predictions of these different models.

Our paper is structured as follows: In Sect. 2 we introduce our main datasets: both the KiDS and GAMA galaxy surveys which are used to perform the GGL measurements, and the MICE and BAHAMAS simulations & mock galaxy catalogues to which we compare our results. Sect. 3 describes our analysis of these (mock) datasets as we select our isolated foreground galaxy sample, perform the GGL measurements, and translate the results into the RAR. Sect. 4 contains a description of the theoretical predictions to which we compare our observations: MOND, EG and the N17 analytical DM model. In Sect. 5 we present the resulting RAR measurements and model comparison. Sect. 6 contains the discussion and conclusion.

Throughout this work we adopt the WMAP 9-year (Hinshaw et al. 2013) cosmological parameters : $\Omega_{\rm m} = 0.2793$, $\sigma_8 = 0.821$, $\Omega_\Lambda = 0.7207$, and $H_0 = 70\,{\rm km\,s^{-1}Mpc^{-1}}$, which were used as the basis of the BAHAMAS simulation. The cosmological parameters used in creating the MICE-GC simulations are: $\Omega_{\rm m} = 0.25$, $\sigma_8 = 0.8$, $\Omega_\Lambda = 0.75$, and $H_0 = 70\,{\rm km\,s^{-1}Mpc^{-1}}$. Throughout the paper we use the reduced Hubble constant $h_{70} \equiv H_0/(70\,{\rm km\,s^{-1}Mpc^{-1}})$.

2 DATA

2.1 KiDS source galaxies

Write the beginning. Need to know:

- What changes as we go to KiDS-1000 (K1000 paper?).

2.2 GAMA foreground galaxies

Write everything.

2.3 KiDS foreground selection

Still need to know:

- Maciek's GL-KiDS selection criteria for K1000.
- Angus' stellar mass method for K1000.

2.4 MICE mock galaxies

In order to compare our observations to predictions from ΛCDM, we adopt two different DM simulations. One of these is the MICE-GC N-body simulation (Fosalba et al. 2015b), which contains $\sim 7{\times}10^{10}$ DM particles in a $(3072\,h_{70}^{-1}{\rm Mpc})^3$ comoving volume. From this simulation the MICE collaboration constructed a $\sim 5000\,{\rm deg}^2$ lightcone, with a maximum redshift of $z = 1.4$. The Friends of Friends (FOF) DM halos in this lightcone were populated with galaxies using a hybrid Halo Occupation Distribution (HOD) and Halo Abundance Matching (HAM) prescription (Carretero et al. 2015; Crocce et al. 2015). Halos are considered 'resolved' down to 20 particles, corresponding to a halos with a mass of $6\times10^{11}\,h_{70}^{-2}{\rm M}_\odot$ which host galaxies with an absolute magnitude < -18.9 (*should we apply a cut here?*). Every galaxy has a set of sky coordinates, a redshift and comoving distance. In addition, each galaxy is assigned a stellar mass (*how was this determined*)

2.5 Bahamas mock galaxies

Written by Kyle?

3 DATA ANALYSIS

3.1 Isolated galaxy selection

Write the beginning. Still need to know:

- how to test the isolation criterion.

3.2 Lensing measurement

Write the beginning. Still need to know:

- How (if?) the GGL-pipeline changes with K1000.

We recognize that, by using the unadulterated GGL equations to measure the (apparent) density distribution around foreground galaxies, we necessarily assume that the laws of GR hold with respect to the deflection of light by a gravitational potential.

3.3 Conversion to radial acceleration

Still need to know: whether we will use the SIS assumption or linear interpolation.

- Test both methods using the Bahamas simulation.

4 THEORETICAL PREDICTIONS

4.1 Modified Newtonian Dynamics

Write everything.

4.2 Emergent Gravity

Write everything.

4.3 Analytical CDM model

Written by Kyle?

5 RESULTS

Write when the results are ready. I still need:

- The K1000 lensing catalogues with ANNz redshifts and stellar masses.
- The results from the Bahamas simulation.

5.1 Isolated galaxies

6 DISCUSSION AND CONCLUSION

Write at the end.

ACKNOWLEDGEMENTS

Write at the end.

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