Linearity: galaxy formation encounters an unanticipated empirical relation

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ABSTRACT

Measurements from galaxies spanning a broad range of morphology reveal a linear scaling of enclosed dark to luminous mass that is not anticipated by standard galaxy formation cosmology. The linear scaling is found to extend from the inner galactic region to the outermost data point. Uncertainties in the linear relation are narrow, with \( \text{rms} = 0.31 \) and \( \sigma = 0.31 \). It is unclear what would produce this linearity of enclosed dark to luminous mass. Baryonic processes are challenged to account for the linear scaling, and no dark matter candidate possesses a property that would result in a linear relation. The linear scaling may indicate new dark matter candidates, or an astrophysical process beyond standard galaxy formation theory.

Key words: galaxies:formation – dark matter – galaxies:kinematics and dynamics – galaxies:haloes – galaxies:structure

1 INTRODUCTION

According to standard cosmological theory, galaxies formed in the early universe within the potential wells of dark matter haloes (White & Rees 1978; Blumenthal et al. 1984; Freeman 2003; Bromm et al. 2009). In a process of hierarchical galaxy formation, small haloes merged with larger haloes to form the galaxies, groups, and clusters observed in the present universe.

In standard cosmology, dark matter haloes are comprised of theoretical particles that neither emit, nor absorb, nor reflect radiation at any wavelength. Well motivated dark matter candidates include Weekly Interacting Massive Particles (WIMPs; Iwanus et al. 2019; Cook et al. 2020; Basu et al. 2021; Thorpe-Morgan et al. 2021), warm dark matter (Chatterjee et al. 2019; Gilman et al. 2020; Garzilli et al. 2021; Herrmans et al. 2021), self-interacting dark matter (Despali et al. 2019; Robles et al. 2019; Robertson et al. 2021; Correa 2021), axions (Leong et al. 2019; Galanti et al. 2020; Bauer et al. 2021; Giare et al. 2021), and primordial black holes (Carr & Silk 2018; Stegmann et al. 2020; Kim 2021; Sureda et al. 2021).

Discrepancies, however, have been noted between dark matter simulations and observations (see Bullock & Boylan-Kolchin 2017, for a review). In contrast to cuspy cores predicted by dark matter models (Navarro et al. 1996; Moore et al. 1998), nearly constant density cores are found in a wide range of galaxies (e.g. Binney & Evans 2001; Keeton 2001; De Blok et al. 2001; Gentile et al. 2007; Spano et al. 2008; Bekki & Stanimirović 2009; Amorisco et al. 2013; Rodrigues et al. 2017).

Dark matter simulations also predict the majority of the most massive subhaloes of the Milky Way are too dense to host any of its bright satellites (Boylan-Kolchin et al. 2011; Di Cintio et al. 2011; Garrison-Kimmel et al. 2014).

In addition to tensions between dark matter simulations and observations, an empirical relation between dark and luminous mass has been suggested through analysis of a small number of galaxies (Lovas & Kielkopf 2014) including elliptical galaxy NGC4636. Enclosed total mass of NGC4636 increases continuously to the outermost data point even as its luminous mass converges toward a limiting mass (Fig. 1 upper panel; Schuberth et al. 2006). The authors do not quantify the uncertainties since they are mostly of a systematic nature. As total enclosed mass of NGC4636 increases continuously, the ratio of enclosed dark to luminous mass scales linearly with radius. The linear scaling reaches from the inner galactic region to the outermost data point (Fig. 1 lower panel). It is unclear what would produce this close linear relation. No dark matter candidate possesses a theoretical property that would lead to a linear scaling.

To ameliorate dark matter tensions, modifications have been proposed to the laws of gravity, notably MOND (Milgrom 1983). MOND, however, is in strong disagreement with gravitational lensing measurements (Clowe et al. 2006) and conflicts with observations on scales ranging from dwarf galaxies (Sánchez-Salcedo et al. 2013) to galaxy clusters (Pointecouteau & Silk 2005).

The core-cusp and too-dense subhalo discrepancies could be mitigated through baryonic processes such as star formation and supernova feedback (Governato et al. 2012; Zolotov et al. 2012; Madau et al. 2014; Chan et al. 2015; Wetzel et al. 2016; Dashyan et al. 2018). Baryonic processes, however, are challenged to account for the linear scaling of enclosed dark to luminous mass. The profile of dark and luminous mass is unique to each galaxy due to the galaxy’s individual size, morphology, and quantity of dark and luminous mass. To produce a linear scaling of enclosed dark to luminous mass, star formation and supernova feedback processes would require individual tuning to each galaxy.

It would be of interest to determine if the linear scaling of enclosed dark to luminous mass exhibited by pressure supported galaxy NGC4636 would be found also in a sample of rotationally supported galaxies.

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Figure 1. Enclosed mass of pressure supported E0 galaxy NGC4636. Upper panel plots the profiles of luminous, dark, and total mass. Velocities of 174 globular clusters are used as dynamical tracers. Lower panel shows the ratio of NGC4636 enclosed dark mass to luminous mass as a function of radius. The ratio of enclosed dark to luminous mass scales linearly with radius. Solid black line delineates the slope of the linear relation. The slope value $m$ is noted in the upper left corner of the panel together with the correlation coefficient $r$. Slope is derived using the least squares method with intercept taken to be zero.

2 LINEARITY OF ROTATIONALLY SUPPORTED GALAXIES

To examine whether a linear scaling of enclosed dark to luminous mass might also be found in rotationally supported galaxies, we sample four galaxies from the Spitzer Photometry & Accurate Rotation Curves (SPARC) catalogue of 175 galaxies (Lelli et al. 2016).

Figure 2 plots enclosed mass of the four galaxies. The upper section of panels (a)-(d) displays the ratio of enclosed dark to luminous mass as a function of radius. With all four galaxies, the ratio of enclosed dark to luminous mass follows a linear relation. Solid black lines delineate the slope of that relation. The slope value $m$ is noted in the upper left corner together with the correlation coefficient $r$.

The lower section of panels (a)-(d) plots the profiles of luminous, dark, and total mass for the four galaxies. The linear scaling of enclosed dark to luminous mass as a function of radius is more readily observed. For NGC1705 and UGC05414, panels (a) and (d) respectively, the mass profiles are dissimilar. Never the less, the ratio of enclosed dark to luminous mass scales as $r$ in both galaxies.

By contrast, the mass profiles are similar for UGC05414, Fig. 2(d), and for NGC4636, Fig. 1. NGC4636, however, is a pressure supported elliptical of E0 morphology, whereas UGC05414 is a rotationally supported irregular of IABm morphology. The radius of NGC4636 exceeds that of UGC05414 by a factor of 12, and its mass exceeds that of UGC05414 by a factor $>2$ dex. None the less, for both galaxies, the radial scaling of enclosed dark to luminous mass follows a linear relation.

Consistent with NGC4636 (Fig. 1), in each galaxy of Fig. 2, the radial mass profile of dark matter scales with luminous mass to produce a linear scaling of enclosed dark to luminous mass. With each galaxy the linear scaling extends from the inner region to the last kinematic data point.

To place the galaxies of Fig. 2 on a uniform scale, their radii are normalised by applying slope $m$ to $r$, such that $mr = r_{\text{norm}}$.

With radii normalised, the ratio of enclosed dark to luminous mass is re-plotted in panels (e)-(h). From left to right the data points are over-plotted upon the previous panel. The ratio of enclosed dark to luminous mass for the four galaxies scales proportionally with radius. With radius normalised, the slope of proportionality is unity, solid black line, panels (e)-(h).

Four galaxies from the SPARC catalogue exhibit in Fig. 2 a linear scaling of enclosed dark to luminous mass. To identify if such linearity would extend to the broad database, we evaluate a large sample of galaxies from the catalogue.

2.1 Analysis of the SPARC data

The SPARC catalogue of 175 galaxies uses near-infrared (3.6 $\mu$m) surface photometry from NASA’s Spitzer space telescope to trace the distribution of stellar mass. Galaxies in the catalogue range in morphology from S0 to Sd to Irr. H$\alpha$ and H I measurements from 54 published sources are incorporated into the database. Numerous researchers have drawn upon the catalogue for their work. (e.g. Bernal et al. 2018; Santos-Santos et al. 2018; Naik et al. 2019; Tortora et al. 2019; Ponomareva et al. 2021). The complete database is located at http://astroweb.cwru.edu/SPARC.

The compilers of the database describe in detail the methods they employed to determine stellar, gas, and observed rotation velocities through the application of 3.6 $\mu$m surface brightness profiles, H I surface density profiles, and H I / H$\alpha$ rotation curves (Lelli et al. 2016). SPARC data on the stellar components are for stellar mass-to-light ratios. When a bulge is present, the stellar rotation velocity is further decomposed into bulge and disk. A bulge is present in 32 of the SPARC galaxies. For the gas contribution, a thin disk is assumed. SPARC data adjust H I measurements by a factor 1.33 to account for helium. Increasing the H I factor to 1.4 to account for both helium and metals produces no impact on the results presented here.

Gentile et al. (2004) determine that luminous matter of several galaxies now in the SPARC catalogue is distributed as a thick disk. Hallenbeck et al. (2014) find that for other galaxies now in the SPARC database, varying the thin stellar disk to allow for finite thickness has little or no effect. For consistency, the present paper adopts the thin disk geometry. Beyond $r_{\text{norm}}$ = 1 spherical dark mass is the dominant mass component. Dark mass is ascribed to the amplitude of rotation velocity unaccounted for by the luminous components, where

$$v_{\text{obs}}^2(r) = v_{\text{lum}}^2(r) + v_{\text{dark}}^2(r).$$  (1)

In Equation (1) velocity of the luminous contribution encompasses three components: the stellar disk $V_{\text{disk}}$, stellar bulge $V_{\text{bul}}$, and gas disk $V_{\text{gas}}$, such that

$$v_{\text{lum}}^2(r) = Y_s v_{\text{disk}}^2(r) + Y_s v_{\text{bul}}^2(r) + v_{\text{gas}}^2(r),$$  (2)

where $Y_s$ is the stellar mass-to-light ratio.

With 48 of the 175 SPARC galaxies, $V_{\text{gas}}$ is negative in the inner
regions. This occurs when the gas distribution has a central depression and material in the outer areas exerts a stronger gravitational force than in the inner regions (Lelli et al. 2016). For those data points with negative $V_{\text{gas}}$, velocity of the luminous contribution takes the form

$$V_{\text{lum}}^2(r) = Y_s V_{\text{disk}}^2(r) + Y_b V_{\text{bul}}^2(r) - V_{\text{gas}}^2(r).$$

(3)

$V_{\text{gas}}$ is negative for 361 of the 3391 data points in the SPARC database.

Meidt et al. (2014) report that at 3.6 $\mu$m a single $Y_s = 0.6 M_\odot/L_\odot$ is feasible for a Chabrier initial mass function. The present study adopts a single $Y_s = 0.6 M_\odot/L_\odot$ at 3.6 $\mu$m for all galaxies in the SPARC catalogue. The value $Y_s = 0.6 M_\odot/L_\odot$ is applied uniformly to both the stellar disk and stellar bulge. A single $Y_s = 0.6 M_\odot/L_\odot$ results in negative dark mass at 244 of the 3391 data points. To preclude a negative ratio of dark to luminous mass, negative dark mass is assigned a value of zero in the analysis. If negative dark mass were permitted, $\sigma$ would increase 0.01 and rms would increase 0.01.

2.2 Selection of data from the SPARC catalogue

Typical of an extensive database, measurements within the SPARC catalogue vary in certainty. To varying degrees, for example, the galaxies in the catalogue display asymmetries, non-circular motions, and off-sets between H I and stellar distributions (Lelli et al. 2016). Twelve such galaxies are identified by Lelli et al. (2016) to be of low quality. If these 12 galaxies are removed from the database, $\sigma$ increases 0.004 and rms increases 0.004.

Accuracy of H I rotation curve measurements diminishes in nearly face-on galaxies, where inclination $i < 40^\circ$ (Kormendy & Freeman 2016). Within the catalogue of 175 galaxies there are 12 face-on galaxies with $i < 30^\circ$, 22 galaxies with $i < 35^\circ$, and 28 galaxies with $i < 40^\circ$. If the 12 face-on galaxies with $i < 30^\circ$ are removed from the database, $\sigma$ decreases 0.006 and rms decreases 0.006.

For 3082 of 3391 data points in the catalogue, circular velocity uncertainty is $\leq 15\%$. Improving the uncertainty to $\leq 10\%$ reduces the data points to 2807; improving the uncertainty to $\leq 5\%$ reduces the data points to 1967.

To maximise the data set and minimise assumptions, the present study excludes none of the 175 galaxies in the catalogue and removes none of the 3391 data points.
Whether producing a flat rotation curve. In the SPARC catalogue, 40 of the 175 galaxies do not exhibit a flat rotation curve. Whether producing a flat or non-flat rotation curve, the distribution of dark matter particles in the studied galaxies results in a linear scaling of enclosed dark to luminous mass that extends from the inner region to the outermost data point. Such linear scaling is not anticipated by standard hierarchical galaxy formation theory: the merger of small haloes into larger haloes is designed to explain structure rather than to produce a linear relation; accordingly a linear scaling of enclosed dark to luminous mass has not been reported as an outcome of any galaxy formation model. It is uncertain what would produce this linear relation. Baryonic processes are challenged to account for the linear scaling, and no dark matter candidate possesses a theoretical property that would result in a linear relation.

The empirical linear relation may be used to test and constrain galaxy formation models using the closeness of the observed relation as a benchmark.

The linearity of enclosed dark to luminous mass may indicate the existence of new dark matter candidates, or the presence of an astrophysical process beyond standard galaxy formation cosmology.

3 RESULTS

To evaluate the scaling of enclosed dark to luminous mass in a broad range of galaxies, we examine the full set of 175 galaxies in the SPARC catalogue. Figure 3 shows the scaling of enclosed dark to luminous mass as a function of normalised radius for the full data set. The 3391 data points are binned at approximate intervals of 1.0 $r_{\text{norm}}$, with the last bin extended to include outliers. Filled squares denote the mean of binned data. Error bars represent 1σ of data in each bin. The error bar for 1σ = 0.21 in the first bin is not visible. Solid red line corresponds to a linear scaling of enclosed dark to luminous mass. Inset shows the histogram of all residuals and a Gaussian of width $\sigma = 0.31$. Lower panel displays the residuals as a function of $r_{\text{norm}}$. Error bars on the binned data represent 1σ.

![Figure 3. Ratio of enclosed dark to luminous mass as a function of normalised radius for the complete set of 175 SPARC galaxies.](image)

The complete set of 3391 data points spanning 175 galaxies evinces a linear scaling of enclosed dark to luminous mass. Uncertainties are quantified by rms and $\sigma$, with rms = 0.31 and $\sigma = 0.31$. For all 3391 data points, the correlation coefficient $r = 0.9838$.

In the outer region of disc galaxies the radial mass profile of the dark matter scales linearly with the luminous mass to commonly produce a flat rotation curve. In the SPARC catalogue, 40 of the 175 galaxies do not exhibit a flat rotation curve. Whether producing a flat or non-flat rotation curve, the distribution of dark matter particles nor reflect radiation at any wavelength. Well motivated dark matter candidates include WIMPs, warm dark matter, self-interacting dark matter, axions, and primordial black holes.

Measurements from 175 galaxies spanning a broad range of morphology reveal a linear scaling of enclosed dark to luminous mass that is not anticipated by standard galaxy formation cosmology. In the framework of standard galaxy formation theory, the linear scaling of enclosed dark to luminous mass would require tuning the dark matter profile of each galaxy. Such tuning would be required whether the dark matter consisted of WIMP dark matter, warm dark matter, primordial black holes, axions, self-interacting dark matter, or a combination of dark matter candidates.

In the studied galaxies, wherever dark mass is found–throughout a spherical E0 galaxy, within the arms of spiral galaxies, in the ill-defined structure of irregular galaxies–the dark matter is distributed in such a way as to produce a linear scaling of enclosed dark to luminous mass. No dark matter candidate possesses a theoretical property that would result in a linear relation. Further work will lead to dark matter properties or astrophysical processes that could produce the close linear relation.

4 SUMMARY

Standard cosmological theory posits that galaxies formed in the early universe within the potential wells of dark matter haloes. Small haloes merged with larger haloes to form the galaxies, groups, and clusters of the present universe. In standard cosmology, dark matter haloes are comprised of theoretical particles that neither emit, nor absorb, nor reflect radiation at any wavelength. Well motivated dark matter candidates include WIMPs, warm dark matter, self-interacting dark matter, axions, and primordial black holes.

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DATA AVAILABILITY

The data underlying this article are available in the Zenodo repository, at https://doi.org/10.5281/zenodo.6416252.
REFERENCES

Amorisco N. C., Agnello A., Evans N. W., 2013, MNRAS, 429, L89
Basu A., Roy N., Choudhuri S., Datta K. K., Sarkar D., 2021, MNRAS, 502, 1605
Bauer J. B., Marsh D. J. E., Hložek R., Padmanabhan H., Laguë A., 2021, MNRAS, 500, 3162
Bekki K., Stanimirović S., 2009, MNRAS, 395, 342
Bernal T., Fernández-Hernández L. M., Matos T., Rodríguez-Meza M. A., 2018, MNRAS, 475, 1447
Binney J. E., Evans N. W., 2001, MNRAS, 327, L27
Blumenthal G. R., Faber S. M., Faber M. J., 1984, Nature, 311, 517
Boylan-Kolchin M., Bullock J. S., Kaplinghat M., 2011, MNRAS, 415, L40
Bromm V., Yoshida N., Hernquist L., McKee C. F., 2009, Nature, 459, 49
Bullock J. S., Boylan-Kolchin M., 2017, ARA&A, 55, 343
Carr B., Silk J., 2018, MNRAS, 478, 1376
Chan T. K., Kereš D., Oñorbe J., Hopkins P. F., Muratov A. L., Faucher-Giguère C. A., Quataert E., 2015, MNRAS, 454, 2981
Chatterjee A., Dayal P., Choudhury T. R., Huter A., 2019, MNRAS, 487, 3560
Clowe D., Bradac M., Gonzalez A. H., Markevitch M., Randall S. W., Jones C., Zaritsky D., 2006, ApJ, 648, L109
Cook R. H. W., et al., 2020, MNRAS, 494, 135
Correa C. A., 2021, MNRAS, 503, 920
Dashyan G., Silk J., Mamon G. A., Dubois Y., Hartwig T., 2018, MNRAS, 473, 5698
De Blok W. J. G., McGaugh S. S., Bosma A., Rubin V. C., 2001, ApJ, 552, L23
Despali G., Sperre M., Veggetti S., Vogelsberger M., Zavala J., Marinacci F., 2019, MNRAS, 484, 4563
Di Cintio A., Knebe A., Libeskind N. I., Yepes G., Gottlöber S., Hoffman Y., 2011, MNRAS, 417, L74
Freeman K. C., 2003, Sci, 302, 1902
Galanti G., Roncadelli M., De Angelis A., Bignami G. F., 2020, MNRAS, 493, 1553
Garrison-Kimmel S., Boylan-Kolchin M., Bullock J. S., Kirby E. N., 2014, MNRAS, 444, 222
Garzilli A., Magalich A., Ruchayskiy O., Boyarsky A., 2021, MNRAS, 502, 2356
Gentile G., Salucci P., Klein U., Vergani D., Kalberla P., 2004, MNRAS, 351, 903
Gentile G., Salucci P., Klein U., Granato G. L., 2007, MNRAS, 375, 199
Giaré W., Di Valentino E., Melchiorri A., Mena O., 2021, MNRAS, 505, 2703
Gilman D., Birrer S., Nierenberg A., Treu T., Du X., Benson A., 2020, MNRAS, 491, 6077
Governato F., et al., 2012, MNRAS, 422, 1231
Hallenbeck G., et al., 2014, AJ, 148, 69
Hermans J., Banik N., Weniger C., Bertone G., Louppe G., 2021, MNRAS, 507, 1999
Iwanus N., Elahi P. J., List F., Lewis G. F., 2019, MNRAS, 485, 1420
Keeton C. R., 2001, ApJ, 561, 46
Kim H., 2021, MNRAS, 504, 5475
Kormendy J., Freeman K. C., 2016, ApJ, 817, 84
Lelli F., McGaugh S. S., Schombert J. M., 2016, AJ, 152, 157
Leong K.-H., Schive H.-Y., Zhang U.-H., Chiueh T., 2019, MNRAS, 484, 4273
Lovas S., Kielkopf J. F., 2014, AJ, 147, 135
Madau P., Shen S., Governato F., 2014, ApJ, 789, L17
Meidt S. E., et al., 2014, ApJ, 788, 144
Milgrom M., 1983, ApJ, 270, 365
Moore B., Governato F., Quinn T., Stadel J., Lake G., 1998, ApJ, 499, L5
Naik A. P., Puchwein E., Davis A.-C., Sijacki D., Desmond H., 2019, MNRAS, 489, 771
Navarro J. F., Frenk C. S., White S. D. M., 1996, ApJ, 462, 563
Pointecouteau E., Silk J., 2005, MNRAS, 364, 654
Ponomareva A. A., et al., 2021, MNRAS, 508, 1195

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