OUTER GALACTIC DISKS AND A QUANTITATIVE TEST OF GRAVITY AT LOW ACCELERATIONS

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ABSTRACT
We use the recent measurement of the velocity dispersion of star-forming, outer-disk knots by Herbert-Fort et al. in the nearly face-on galaxy NGC 628, in combination with other data from the literature, to execute a straightforward test of gravity at low accelerations. Specifically, the rotation curve at large radius sets the degree of non-standard acceleration and then the predicted scale height of the knots at that radius provides the test of the scenario. For our demonstration, we presume that the He knots, which are young (age < 10 Myr), are distributed like the gas from which they have recently formed and find a marginal (>97% confidence) discrepancy with a modified gravity scenario given the current data. More interestingly, we demonstrate that there is no inherent limitation that prevents such a test from reaching possible discrimination at the >4σ level with a reasonable investment of observational resources.

Key words: galaxies: kinematics and dynamics – gravitation

1. INTRODUCTION
The application of the Newtonian law of gravity to the dynamics of galaxies and galaxy clusters leads to the well-known discrepancy between the inferred dynamical mass and the directly observed mass (cf. Zwicky 1933; Smith 1936; Rogstad & Shostak 1972; Rubin et al. 1978). This discrepancy, i.e., that the vast majority of matter in the universe is of some undetermined composition, is, in turn, the motivation for the dark matter hypothesis, which is, in turn, the motivation for the dark matter hypothesis, and this requires identifying a regime in which the two hypotheses make distinctly different predictions. There are some basic requirements for whatever environment one envisions when constructing such a test. First, one will need to work in a regime well beyond the scale where Newtonian gravity first appears to fail. Second, one will need to work in a regime appropriate for the proposed modified gravity model. Because the currently proposed modifications to Newtonian gravity are not yet complete theories, there is little to be gained by invalidating a specific gravitational variant beyond its intended working parameters. Third, one will need to identify an environment in which the physical distributions of the baryons and hypothesized dark matter are sufficiently different that they create distinct gravitational signatures. Lastly, one will need to identify a dynamically simple environment where the interpretation does not depend on one’s understanding of a complex dynamical history.

All of these requirements drive us to study the outskirts of disk galaxies. The observed outer-disk rotation curves provide one of the principal arguments for deviations from Newtonian gravity (if one assumes no dark matter, e.g., modified Newtonian dynamics or MOND; Milgrom 1983; Begeman et al. 1991; McGaugh & de Blok 1998) and so satisfy the first and second criteria. The third and fourth criteria are also satisfied in that the baryons in at least some outer disks have been shown to lie in a dynamical cold, undisturbed disk (Christlein & Zaritsky 2008; Herbert-Fort et al. 2010), and the dark matter, while not in a perfectly spherical distribution, is thought to lie in a significantly rounder one (Hoekstra et al. 2004; Mandelbaum et al. 2006).

For motions in the disk plane, the modified gravity and dark matter hypotheses are degenerate with both predicting larger rotational velocities than inferred from the luminous matter using Newtonian gravity. The kinematics in the vertical direction, where the baryons are strongly concentrated toward the disk plane, but the posited dark matter is not, provides the discrimination between the two hypotheses. Such a test was implemented by Sánchez-Salcedo et al. (2008) using the thickness of the H i disk at large radii in our own Galaxy. While they find a modest discrepancy with the MONDian prediction, they note that the comparison is somewhat compromised by other potential sources of support for the gaseous layer, such as magnetic fields, cosmic rays, or supernovae injected energy. Because one needs to find thicker than predicted H i to invalidate MOND, and because uncertain sources of support will act to thicken the gas distribution, this test has an unresolved weakness. We propose to work in the same environment, which has so many appealing features, but to utilize another tracer population that cannot be supported by magnetic fields, cosmic rays, or injected energy. In this Letter, we explore the implications of the measured dynamics of outer-disk star-forming knots (Ferguson et al. 1998; Thilker et al. 2005; Zaritsky & Christlein 2007) on modified gravity models.

2. TESTING THE MOND PARADIGM
The vertical structure of galactic disks in modified Newtonian dynamics has been explored by a number of authors (e.g., Famaey & Binney 2005; Nipoti et al. 2007; Sánchez-Salcedo et al. 2008). Using the phenomenological equation (Bekenstein & Milgrom 1984)

$$\nabla \cdot \left[ \frac{\mu}{a_0} \left| \nabla \Phi \right| \right] \nabla \Phi = 4\pi G \rho \tag{1}$$

[922]
for the gravitational field $\Phi$, where $\mu(\nabla \Phi)$ is the phenomenological factor that depends on the magnitude of the local acceleration, $g \equiv |\nabla \Phi|$, in units of the MOND scale $a_0 \approx 10^{-8}$ cm s$^{-2}$, Sánchez-Salcedo et al. (2008) showed that the disk scale height in the deep MOND regime is implicitly given by

$$\frac{1}{2} L(x) \left( \frac{v_c^2}{R} \right)^2 \frac{\pi G}{\mu(x)} h^2 + \pi \frac{\Sigma L}{M_L} h - \sigma^2 = 0. \tag{2}$$

In the above expressions, $G$ is the gravitational constant, $\sigma$ is the velocity dispersion, $\sigma$ is the circular velocity of matter, $R$ is the galactocentric radius, and $L(x)$ is the logarithmic derivative of $\mu$ at $x$, where $x \equiv g/a_0$. Various fitting functions for $\mu(x)$, with the appropriate limiting behavior, have been developed, including what is often called the standard one, $\mu = x/\sqrt{1 + x^2}$ (cf. Begeman et al. 1991), and $\mu = x/(1+x)$ (Famaey & Binney 2005).

We estimate the magnitude of the phenomenological factor $\mu$ at the radius of the knots using the equation for the radial acceleration

$$\mu(x) v_c^2 = \frac{G M_L}{R}, \tag{3}$$

where $v_c$ is the circular velocity of matter and $M_L$ is the enclosed mass of luminous matter. This equation is valid for a spherical distribution of mass $M_L$. In fact, we discuss a thin disk of baryonic material with a surface brightness (and corresponding mass column density) that exponentially declines with radius, as is typical for spiral galaxies. For such a mass distribution the predicted circular velocity is somewhat larger than that of a spherical distribution of equivalent enclosed mass (cf. Binney & Tremaine 1987), which implies an even lower value of $\mu$ and hence a stronger MOND effect. However, for large $R$ the difference is small, <10% at $R > 5$ disk radial scale lengths. We confirm, using the standard fitting formula for $\mu(x)$, that Equation (3) produces a somewhat larger value of $\mu$ than the fitting formula (0.38 versus 0.32, respectively) and therefore a correspondingly somewhat larger value of $h$—which is conservative given the argument we are constructing. Combining Equations (2) and (3), we obtain

$$\frac{1}{2} L(x) \left( \frac{v_c}{R} \right)^2 \frac{\pi \Sigma L}{M_L} h^2 + \pi - \sigma^2 = 0, \tag{4}$$

which we solve for $h$.

The test is then a simple comparison of the predicted and observed values of $h$, which requires knowledge of the six measurable quantities: $h$, $M_L$, $\sigma$, $R$, $\Sigma_L$, and $v_c$. The more difficult of these to measure are $h$ and $\sigma$, and in particular it is difficult to measure both quantities for any one galaxy because $h$ is best measured in inclined systems while $\sigma$ is best measured in face-on systems. One can combine characteristic values of $h$ and/or $\sigma$ to stand in place of the value for an individual galaxy in order to pursue this test. Of the two quantities, the one that has been measured in a number of systems is the scale height, $h$ (O’Brien et al. 2010), although only for the H I layer and not yet for the knots themselves. This shortcoming must eventually be remedied because otherwise our test is also susceptible to the unknown heating sources mentioned previously. Because the test has a stronger sensitivity to $\sigma$, we present a measure of $\sigma$ in the nearly face-on galaxy NGC 628 and use a representative estimate of $h$ for disk galaxies.

3. THE DATA

We now describe how we estimate each of the quantities necessary to evaluate Equation (4).

3.1. The Disk Scale Height, $h$

The only currently available measurement of the scale height of outer disks comes from measurements of the H I flaring (Sancisi & Allen 1979; Merrifield 1992; Olling 1996; O’Brien et al. 2010). These of course (in the current context) have the same weakness described by Sánchez-Salcedo et al. (2008) in that the thickness may be due to effects other than thermal pressure. Nevertheless, the currently definitive study of O’Brien et al. (2010) shows that the typical scale height at the radii of interest here is $\sim 1$ kpc. Their results also show a universal, steep rise in $h$ toward the edge of the H I disk, suggesting that this test can become increasingly powerful at larger radii or that additional heating occurs near the edge of the neutral gas disk. Of the galaxies studied, IC 2531 is the nearest analog to NGC 628. They are both classified as Sc in NASA/IPAC Extragalactic Database (NED). The V-band magnitudes are $-20.9$ and $-20.2$, respectively. The H I extents are in both cases $\sim 30$ kpc and the rotation speeds are 220 and 170 km s$^{-1}$. At the corresponding mean radius of our observations (18 kpc; see below), $h = 1.2$ kpc. The value of $h$ as a function of radius for the two galaxies in their sample with circular velocity $v_c > 100$ km s$^{-1}$ is the same, except for the final steep rise just before the end of the H I data. The uncertainty, judging from the scatter in $h$ as a function of $R$ and a comparison of the two more massive galaxies in the sample, appears quite small ($\sim 10\%$). The more serious, but not easily quantified, uncertainties relate to how well these galaxies describe NGC 628 and how well does the H I scale height describe that of the knots. With a typical velocity of 11 km s$^{-1}$, Hα-emitting knots will travel about 100 pc in their lifetime, significantly less than one scale height.

The future of this test lies in directly measuring the scale height of the star-forming knots. This can be done with either deep Galaxy Evolution Explorer (GALEX) or Hα observations of edge-on galaxies, but has not yet been attempted. The value of the GALEX knots is that in their lifetime (> several hundred Myr) they will have completed several vertical oscillations and will therefore test whether the H I and knots settle into the same vertical distribution.

3.2. The Enclosed Mass of Luminous Matter, $M_L$

The luminosity of the galaxy ($M_V = -20.73$, based on $m_V = 9.25$ (NED) and our adopted distance of 9.9 Mpc) is $1.6 \times 10^{10} L_\odot$ for $M_V L_V = 4.79$. For $B-V = 0.51$ and from the relationships for stellar mass-to-light ratios from Bell & de Jong (2001), we estimate $M/L_V = 1.9$ and calculate that the stellar mass is $3.1 \times 10^{10} M_\odot$. The uncertainty in this value will be dominated by that in $M/L$. The integrated magnitude is not likely to be off by more than 0.1 mag, and the scatter in distance models (NED) corresponds to 0.1 mag as well. As a result, the uncertainty in the luminosity cannot exceed 20%. However, $M/L$ could in principle be off by substantially more. Bell & de Jong (2001) estimate, both from the differences obtained with different models and the scatter in their Tully–Fisher relationship, that the random scatter in $\log M/L$ is 0.2 (or about 50% in $M/L$, which is the uncertainty we adopt for $M_L$). To this mass we add the gas as measured by Kamphuis & Briggs (1992). They measured a total H I mass of $12 \times 10^{10} M_\odot$ of which they attribute $3 \times 10^{10} M_\odot$ to the distorted disk that lies
beyond our measured knots. After correcting the remainder for the presence of He by multiplying by 1.4, we estimate a gas mass of $12.6 \times 10^{10} M_\odot$. The total mass we use is then $43.6 \times 10^{10} M_\odot$ with an uncertainty of 50%.

3.3. The Velocity Dispersion, $\sigma$

The observational data consist of the radial velocity measurements of star-forming regions in the outer disk of the nearly face-on galaxy NGC 628. Star-forming regions generate strong emission lines (H$\alpha$ was used in this case) whose redshifts can be measured precisely. We currently have a measurement by Herbert-Fort et al. (2010) of the vertical velocity dispersion in the outer disk of NGC 628 using 14 such regions at galactocentric radii ranging from 1.04 to 1.79$R_{25}$ (13 to 23 kpc). There are three principal sources of uncertainty in this measurement. First, the sample size is small. This could, in principle, be corrected and does not pose an inherent limit on the usefulness of this test. We have an estimate of this random uncertainty, $\sim 4$ km s$^{-1}$, from the work of Herbert-Fort et al. (2010). Second, there is an uncertainty regarding the orientation and kinematic parameters of the disk about which we calculate the dispersion. Again, Herbert-Fort et al. (2010) attempted to explore this uncertainty and concluded that for several of the more plausible orientations the uncertainty in $\sigma$ was about 2 km s$^{-1}$. For the current purpose, we adopt an uncertainty of 4 km s$^{-1}$, but caution that there could be a systematic problem. This possibility should be addressed both with more data on this galaxy and with observations of other galaxies.

A more fundamental limitation of the current data is that we measure the velocity dispersion only for knots that are relatively young ($<10$ Myr) because we require the presence of the H$\alpha$ emission line. This results in our using knots that are closely related to the neutral hydrogen and which have had insufficient time to erase the possible influence of unknown heating sources on the gas. The eventual solution to this problem is to measure the scale height of both this young population of knots and of the older GALEX population. If these two populations share a similar scale height then the concerns of using a young tracer population are alleviated. Otherwise, we will need to somehow measure the velocity dispersion of the older, fainter knots.

3.4. The Radius, $R$

Due to the sparseness of the velocity field sampling, we must use data spanning a range of radii. The mean radius of the Herbert-Fort et al. (2010) data is 18 kpc. The uncertainty in this comes from the uncertainty in the distance, which we estimate to be 10%. The more significant and unquantifiable uncertainty comes from applying this test to data over a range of radii. In the future, a denser sampling of the kinematics will allow us to mitigate against potential systematic errors arising from this averaging (as well as enabling a stronger test by examining the radial behavior of any discrepancies in Equation (4)).

3.5. The Column Density of Luminous Matter, $\Sigma_L$

Over this same region, there are independent measurements of both the gaseous and stellar mass surface densities for NGC 628.\footnote{The numerical values presented here differ from those in Herbert-Fort et al. (2010) because we have “conservatively” chosen to adopt a longer distance, which mitigates the discrepancy between the MONDian prediction and observations.} The H$\text{I}$ gas, measured via the 21 cm line emission (Kamphuis & Briggs 1992), has a mass of $\sim 6 \times 10^9 M_\odot$ over the relevant radial range, resulting in an estimated mean surface gas mass density of $5.6 M_\odot$ pc$^{-2}$ after we multiply by 1.4 to account for He. This estimate of the gas mass excludes molecular gas, which we know is present at some level since there is ongoing star formation. The stellar surface density can be estimated, from the measured surface brightness at $1.3R_{25}$ ($\mu_V \sim 27$ mag arcsec$^{-2}$; Natali et al. 1991) and an estimated $M/L_V$ of 3 for an old stellar population (for $B-V = 1$ and a modified Salpeter initial mass function, see Bell & de Jong 2001), to be $1.0 M_\odot$ pc$^{-2}$. The surface mass density, $\Sigma_L$, is therefore likely to be $> 6.6 M_\odot$ pc$^{-2}$ at the representative radius of 1.3 $R_{25}$.

The uncertainty in this value is difficult to quantify in part because the data are not ours and in part because it is likely to be dominated by systematic errors. Because the H$\text{I}$ mass dominates the sum, the principal source of uncertainty is likely to come from that measurement. We use the mean surface density evaluated over a large area. It would clearly be preferable to have more local measurements of both $\sigma$ and $\Sigma_L$ to avoid such averaging. We will assign the rather large uncertainty of 30% in an attempt to capture these possible errors. Ultimately, this test will require a more refined measurement of $\Sigma_L$ and its uncertainty.

3.6. The Rotational Velocity, $v_c$

The rotation curve is poorly measured because of the galaxy’s low inclination. The rotational velocity at the outermost measured radius, $\sim 12$ kpc, is $\sim 180$ km s$^{-1}$ with no evidence for a decline with radius (Fathi et al. 2007), although the velocity derived from their fitted model at the same radius is 150 km s$^{-1}$. The H$\text{I}$ study by Kamphuis & Briggs (1992) adopted a flat rotation curve with amplitude 200 km s$^{-1}$ and found good agreement with their data (except for a couple of high velocity clouds). We adopt $v_c = 170$ km s$^{-1}$ with an uncertainty of 20%.

4. COMPARISON TO PREDICTIONS

Solving Equation (4) using the discussed measured values for NGC 628 and accounting for uncertainties using Monte Carlo techniques, we find that $h$ is predicted to be $356^{+316}_{-255}$ and $298^{+274}_{-172}$ pc for the standard and Famaey–Binney interpolation formulae, respectively. The observed value of 1.2 kpc is rejected with slightly $>97\%$ confidence in both cases. In a scenario with Newtonian gravity and in which the dark matter is not concentrated in the disk, so that the dominant mass component is the observed baryons, the predicted scale height, given by $h = \sigma^2/G\pi \Sigma_L$, is $1280^{+560}_{-426}$ pc, which is in agreement with the observations.

There are two ways in which we can improve the fidelity of this test. First, we can concentrate on lowering the uncertainties. Several of the terms contribute comparably to the final error, although the error on $\sigma$ is currently the largest. It would be possible to reduce this uncertainty by observing more H$\alpha$ knots and using somewhat higher resolution observations to minimize the importance of the instrumental contribution to the observed deviations. For comparison, the H$\text{I}$ velocity dispersions for the outer disks of the O’Brien et al. (2010) sample are all $\sim 7$ km s$^{-1}$. These results suggest, but do not demonstrate, that the knot $\sigma$’s might be somewhat lower than our measurement. The next largest contribution comes from the uncertainty in the rotational velocity. An analysis of the H$\text{I}$ kinematics in which the rotation is solved for would help address this issue. Second, we can focus at larger radii, where the radial behavior
differences of the modified gravity and dark matter scenarios would provide additional discriminatory power. The difficulty will be measuring $\sigma$ well in a small annulus since the H\alpha knots are somewhat rare. A realistic expectation is that we could reduce all of the uncertainties, except in the distance, by a factor of 2 given a feasible investment of current-day observational resources. In that case, the discrepancy (for the current parameter values) would exceed the 99.99% confidence level.

5. CONCLUSIONS

We present the first use of the kinematics of outer-disk star-forming knots as a test of modifications to gravity at low accelerations. We evaluate the prediction for the disk scale height in modified Newtonian gravity (Sánchez-Salcedo et al. 2008) and compare to the typical H\textsc{i} scale height of the outer disk in similar galaxies. For our estimated uncertainties, we find a marginal (>97% confidence) discrepancy between modified gravity scenarios and the observed scale height, and excellent agreement between a model with Newtonian gravity and a baryonic disk. There remain various aspects of this test that require additional observations to confirm. In particular, measurements of the vertical scale height of the H\alpha-emitting knots and of the older GALEX-identified knots would directly address several potential systematic uncertainties in the current version of the test. If those questions are satisfactorily resolved, we conclude that with additional data this test has the potential to provide strong constraints (>4$\sigma$) on existing alternative gravity models with a relatively modest investment of observational resources.

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REFERENCES

Angus, G. W., Shan, H., Zhao, H. S., & Famey, B. 2007, ApJ, 654, 13
Begeman, K. G., Broeils, A. H., & Sanders, R. H. 1991, MNRAS, 249, 523
Bekenstein, J., & Milgrom, M. 1984, ApJ, 286, 7
Bell, E. F., & de Jong, R. S. 2001, ApJ, 550, 212
Bernabei, R., et al. 2008, Eur. Phys. J. C, 56, 333
Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton, NJ: Princeton Univ. Press)
Christlein, D., & Zaritsky, D. 2008, ApJ, 680, 1053
Clowe, D., Bradač, M., Gonzalez, A. H., Markevitch, M., Randall, S. W., Jones, C., & Zaritsky, D. 2006, ApJ, 648, 109
Famaey, B., & Binney, J. 2005, MNRAS, 363, 603
Fathi, K., Beckman, J. E., Zurita, A., Renzini, M., Knapen, J. H., Daigle, O., Hernandez, O., & Carginan, C. 2007, A&A, 466, 905
Ferguson, A. M. N., Wyse, R. F. G., Gallagher, J. S., & Hunter, D. A. 1998, ApJ, 506, 19
Herbert-Fort, S., Zaritsky, D., Christlein, D., & Kannappan, S. J. 2010, ApJ, 715, 902
Hoekstra, H., Yee, H. K. C., & Gladders, M. D. 2004, ApJ, 606, 67
Kamphuis, J., & Briggs, F. 1992, A&A, 253, 335
Mandelbaum, R., Hirata, C. M., Broderick, T., Seljak, U., & Brinkmann, J. 2006, MNRAS, 370, 1008
McGaugh, S., & de Blok, W. J. G. 1998, ApJ, 499, 66
Merrifield, M. R. 1992, AJ, 103, 1552
Milgrom, M. 1983, ApJ, 270, 371
Natali, G., Pedichini, F., & Riglin, M. 1992, A&A, 256, 79
Nipoti, C., Londrillo, P., Zhao, H., & Ciotti, L. 2007, MNRAS, 379, 597
O’Brien, J. C., Freeman, K. C., & van der Kruit, P. C. 2010, A&A, 515, 63
Olling, R. P. 1996, AJ, 112, 457
Rogstad, D. H., & Shostak, G. S. 1972, ApJ, 176, 315
Rubin, V. C., Ford, W. K., Jr., & Thonnard, N. 1978, ApJ, 255, 107
Sánchez-Salcedo, F. J., Soha, K., & Narayan, C. A. 2008, MNRAS, 385, 1585
Sancisi, R., & Allen, R. J. 1979, A&A, 74, 73
Smith, S. 1936, ApJ, 83, 23
Thilker, D. A., et al. 2005, ApJ, 619, 79
Zaritsky, D., & Christlein, D. 2007, AJ, 134, 135
Zwicky, F. 1933, Helv. Phys. Acta, 6, 110