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MOND and the mass discrepancies in tidal dwarf galaxies

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ABSTRACT

I consider in light of MOND the three debris galaxies discussed recently by Bournaud et al.. These exhibit mass discrepancies of a factor of a few within several scale lengths of the visible galaxy, which, arguably, flies in the face of the cold dark matter paradigm. I show here that the rotational velocities predicted by MOND agree well with the observed velocities for each of the three galaxies, with only the observed baryonic matter as the source of gravity. There is thus no need to invoke a new form of baryonic, yet-undetected matter that dominates the disc of spiral galaxies, as advocated by Bournaud et al.. I argue on other grounds that the presence of such ubiquitous disc dark matter, in addition to cold dark matter, is not likely.

Subject headings: dark matter galaxies: kinematics and dynamics

1. Introduction

Bournaud et al. (2007) have recently reported on three tidal dwarf galaxies that apparently formed in the debris of the collision of two galaxies: possibly of NGC 5291 with another galaxy. For reasons explained cogently by the authors hardly any cold dark matter from the parent galaxies, if it existed there in the first place, is expected to be found in these debris. If this is indeed so, the cold dark matter paradigm (CDM) predicts no mass discrepancy in these dwarfs, contrary to what has been reported by Bournaud et al. (2007): they find in all three dynamical masses within several scale lengths that exceed the the observed baryonic masses by a factor of a few.

The dark-matter (DM) paradigm and MOND (Milgrom 1983a,b, see Sanders & McGaugh 2002, and Bekenstein 2006 for reviews) differ greatly as regards the origin and nature of mass discrepancies they predict in galaxies. In MOND, these discrepancies in a given galaxy are predicted exactly from the presently observed mass distribution, and are oblivious to the exact formation process of the galaxy or the ensuing history. They are predicted, and are observed, to follow some well defined, strict regularities: galactic analogs of Kepler's laws, such as the relation between total baryonic mass and the asymptotic rotation speed (the baryonic Tully Fisher relation), or the onset of the discrepancy at a fixed value of the centrifugal acceleration (see e.g., Milgrom 2002 for a discussion of these predictions, and McGaugh 2006 for a discussion of observational tests). In contrast, in the DM paradigm the mass discrepancies are ratios of total (dark matter plus baryons) to the baryonic mass, and depend strongly on the particular history of the galaxy since the DM and the baryons are subject to different influences. The formation process itself, subsequent cannibalism, mergers, and ejection of baryons by cataclysmic events, such as supernovae, all greatly affect the resulting mass discrepancies. This is why I believe that the CDM paradigm is inherently incapable of ever predicting rotation curves of individual galaxies in the way that MOND does: for most galaxies we simply cannot know the crucial elements of evolution a given galaxy underwent.

The three reported dwarfs, and possibly others like them, are an exception: if they indeed formed as described by Bournaud et al. then their mass discrepancies in CDM can be predicted with some certainty because the collision that led to their formation erased the imprints of earlier history. According to the simulations of Bournaud et al., whatever the DM halo of the parent galaxies was like, as long as it was spheroidal–as predicted by CDM–the debris galaxies would have hardly any DM in them, and should exhibit practically no mass discrepancies. This is also in line with earlier simulations referenced in the online appendices of Bournaud et al., and is easy to understand qualitatively. In contrast, all three dwarfs are predicted by MOND to show appreciable mass discrepancies since they are measured to have low accelerations that are rather deep in the MOND regime. I show below that the MOND predictions are indeed born out by the observations of Bournaud et al.. Gentile et al. (2007a) have recently performed a more detailed analysis, and reach the same conclusions as regards the performance of MOND.

Bournaud et al. consider it a more likely explanation of the mass discrepancy in the dwarfs, that they actually do contain large quantities of yet-undetected matter. They advocate that at least one of the galaxies partaking in the collision that begot the debris had large quantities of DM in their discs–with a mass typically a few times that of the visible baryons. Since this DM cannot be the putative cold dark matter, which form spheroidal halos and does not settle into galactic discs, Bournaud et al. opt for cold molecular hydrogen, which has been considered earlier as the DM in galaxies and clusters (e.g., Pfenniger Combes & Martinet 1994).

In section 2 I describe the MOND results and compare them with the observations. In section 3 I discuss the results and contest the hypothesis of large quantities of disc dark matter in galaxies.

2. MOND rotation curves

To calculate the predicted MOND rotation velocities, V, I use the Newtonian velocities, V_N, read from Fig. 1 of Bournaud et al. (2007) in the MOND relation (Milgrom 1983b)

$$\mu(V^2/ra_0)V^2/r = V_N^2/r.$$

Here $\mu(x)$ is the extrapolating function, which I take here to be $\mu(x) = x(1 + x^2)^{-1/2}$ and I take the acceleration constant of MOND to have the value $a_0 = 1 \times 10^{-8}$cm s^{-2}(e.g. Bottema et al. 2002). Choosing another form of $\mu(x)$ will affect the predictions for the larger radii only a little since the accelerations there are rather smaller than a_0 where μ has to be nearly linear for all forms. The velocities at the inner radii will be affected, but as explained below these anyway depend crucially on the model adopted for the baryon mass distribution.

Figures 1-3 show for each galaxy the Newtonian velocities calculated from the distribution of the visible matter alone as modeled by Bournaud et al., the MONDian speeds calculated from the above equation for the same mass distribution, and the observed rotational speeds. The latter are the average of the approaching and receding velocities as given in Bournaud et al.. (The differences between the two sides are much smaller than the errors.) For clarity's sake I have not marked the error bars for the MONDian speeds since they anyhow all fall within the error bars of the measured values.

In the above procedure I have adopted all the system parameters (the distance, the inclinations of the galaxies, the assumed M/L values for the stellar contributions, etc.) as taken by Bournaud et al., and no attempt was made to improve the agreement by best fitting for these. The baryonic mass of these galaxies are dominated by gas so the exact M/L value is rather immaterial. I have also not corrected for asymmetric drift (i.e., those due to velocity dispersions), which is expected to be rather small for these galaxies (certainly much smaller than the quoted errors). Similarly, I have ignored possible corrections due to the external-field-effect (EFE) in MOND (Milgrom 1983a, Brada & Milgrom 2000a,b, Angus & McGaugh 2007, and Wu et al. 2007). I estimate that it is rather unimportant here (i.e., the acceleration field of NGC 5291 itself, and of other masses, at the dwarfs positions is smaller than the internal accelerations in the dwarfs themselves). Gentile et al. (2007a) study this issue in more detail. They find that indeed the impact of the EFE is marginal inside the last measured point. My own estimate of the EFE due to NGC 5291 is even smaller than theirs. Gentile et al. calculate the far field of NGC 5291 by assuming that the (deprojected) HI line width (ΔV_{20}) given in Malphrus et al. (1997) represents twice the asymptotic rotational speed of that galaxy. This corresponds to a baryonic mass of $3.2 \times 10^{11} M_\odot$, which, the galaxy being rather devoid of gas, corresponds to $M/L_B \approx 16(M/L_B)_\odot$; this is much too high ($\Delta V_{20}/2$

could easily overestimate the asymptotic rotational speed for various reasons; for example, since the galaxy is rather Newtonian in the inner parts, the maximum rotation speed can be quite higher than the asymptotic one). I started from the luminosity of $L_B \approx 2 \times 10^{10} L_\odot$ and assumed $M/L_B \approx 5(M/L_B)_\odot$, appropriate for the color of the galaxy ($B-V \approx 1$). The same mass is gotten with $M/L_K = 1(M/L_K)_\odot$, and it corresponds to a galaxy mass 3.2 times smaller than that effectively used by Gentile et al.. Also, whereas they used the projected distances from NGC 5291 to the dwarfs, taking a mean of 65 kpc as the actual distances, I used 3-D distances using the position of the galaxy with respect to the ring from the model of Bournaud et al.: 114 kpc for N, 118 kpc for S, and 140 kpc for SW (F. Bournaud 2007, private communication). All together my estimates of the field of the galaxy at the position of the dwarfs are 3.2–3.8 times smaller than that of Gentile et al., rendering the effect rather negligible within the presently observed dwarfs.

Bournaud et al. argue convincingly for inclinations around $i = 45^o$ for all three dwarfs stating that they should be almost aligned with the ring they are embedded in. A large part of the indicated errors on the observed velocities reflect the uncertainty in i. This contribution to the errors should than be viewed as an uncertainty in the normalization of the velocity curve, not as errors on individual points. I show in Figure 1 that for one case (NGC 5291N), increasing the inclination to 55^o indeed improves greatly the agreement bringing the MOND velocities into practical coincidence with the observed ones.

Gentile et al. (2007a) suggest that the inclinations of the dwarfs may differ from the model inclinations of 45^o because the EFE induces some precession of the disc. They thus also performed MOND fits with the inclinations left free, and indeed the best fit values differ somewhat from 45^o. This is also shown in my Figure 1 demonstrating that the best value for NGC 5291N is nearer 55^o. This point might require further checking; but, as explained above, my arguably more realistic estimate of the external field effect is rather smaller than theirs and would give an estimate of the precession period that is much longer than the time since the dwarfs formed, so I do not expect this to be an important effect.

3. Discussion

We see that the MOND predictions are in very good agreement with the measured speeds. It should be noted that the baryonic Newtonian curves given in Bournaud et al. are not based on an actual measurement of the observed baryonic distribution. It is based on taking the total amount of observed baryon and assuming a model for their spatial

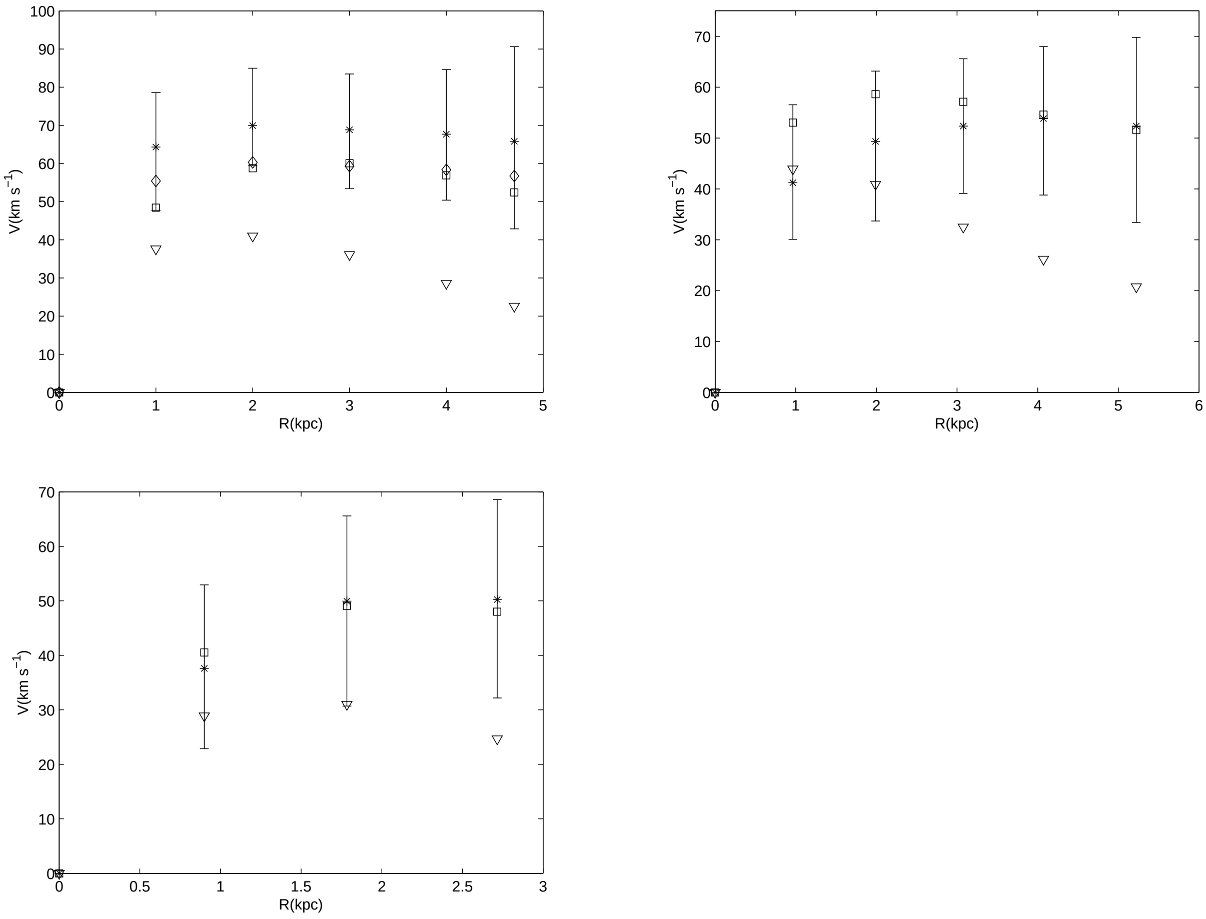

Fig. 1.— The rotation curves for the three dwarfs: NGC 5291N (upper left), and 5291S (upper right), 5291SW (lower left). The measured velocities, assuming the nominal inclination of 45^o, are marked by stars and are shown with their error bars. The calculated Newtonian velocities are marked by inverted triangles. The predicted MOND velocities are marked by squares. The error bars for the last two are omitted for clarity's sake. I also show, for NGC 5291N only, as diamonds, the measured velocities for an assumed inclination of $i = 55^o$.

distribution. The exact values of Newtonian velocities, and hence the MOND values I deduce from them for the inner radii depend on the exact distribution assumed. However, at larger radii, which are already quite beyond the baryonic mass concentration, the velocity values are rather independent of the assumed distribution of baryons. And, after all, this is where the impact of the comparison with both CDM and MOND predictions comes from.

The uncertainties in the analysis of the individual dwarfs are relatively large. This can be traced mainly to the fact that they are much farther than the dwarf spirals of similar properties that have been analyzed before (e.g., de Blok & McGaugh 1998, Gentile et al. 2007b, Milgrom and Sanders 2007). However, while individually, the data is not up to the highest standards, all three dwarfs speak in the same voice: all showing a discrepancy of similar magnitude developing at larger radii, with the observed velocities flattening off in just the way and magnitude predicted by MOND. Thus, the collective conclusion is stronger than the individual ones separately. In addition, the particular importance of these systems lies in their unique potential for differentiating between CDM and MOND.

Bournaud et al. propose another explanation of the mass discrepancy in the three dwarfs: one of the colliding galaxies, which contributed the gas to the debris, also harbored large quantities of some form of DM (not CDM) in its disc, several times more massive than the visible baryons. This DM could then have found its way into the tidal dwarfs, giving rise to the observed mass discrepancy. The candidate they advocate is cold, difficult to detect H_2. Unless we want to assume that the presence of such molecular DM in the disc of the parent galaxy is a rare occurrance, this DM has to be ubiquitous in disc galaxies, as indeed is proposed by Bournauad et al.. They note, however, that this would require a very large conversion factor from the observed CO to H_2: an order of magnitude larger than what is known for galaxies in general (see also the caveats listed by Elmergreen 2007).

I feel that the presence of large quantities of a new component of DM in the disc of spiral galaxies, in addition to the dominant CDM, is unlikely on additional grounds. It is known that the mass and the distribution of the DM in disc galaxies are strongly correlated with those of observed baryons through the relations predicted by MOND. For example, the total mass of the latter, M_{vis}, is strongly correlated with the asymptotic rotational speed, V_∞ (which is determined mostly by the DM) via the MOND relation (Milgrom 1983b)

$$V_\infty^4 = a_0 G M_{vis}.$$

This MOND relation (aka the baryonic Tully-fisher relation) is found to hold over some 5 orders of magnitude in galactic mass (McGaugh 2005,2006). Another correlation is the onset of the mass discrepancy (equality of the contributions of visible and dark matter) at a fixed value, a_0, of the centrifugal acceleration (see McGaugh 2006 for a recent test of this). But the mother of them all is the fact that the visible matter distribution determines the full rotation curve of a galaxy, which in the dark matter paradigm is determined by both components and is dominated by DM in the outer parts. These are all observational facts whatever the interpretation of MOND is. In the context of CDM these correlations require various independent conspiracies between the baryons and the CDM, conspiracies whose origin remains a mystery (see Milgrom 2002 for a more extensive list of these conspiracies and an explanation of why they are independent).

As emphasized many times before, these predicted MOND relations as traditionally formulated are exactly valid only for completely isolated systems. In the presence of an external field these are modified in a manner that is also predicted by MOND (provided the external field is known). However, for many systems the external field effect enters importantly only at rather large radii and leaves a large range of radii for which these predictions are valid with high accuracy (for the Milkey Way it is expected to be important only beyond a few hundred kiloparsecs). The effects of external fields are deemed quite unimportant, as far as I know, for all rotation curve analyses published to date, and hence are also unimportant, for example, in the results of McGaugh 2006 quoted above. Some exceptions concern galaxies in the cores of galaxy clusters, where the external (cluster) fields are of order the of a_0, and low acceleration systems (such as dwarf spheroidals or diffuse globular clusters) in the field of galaxies.

If one now adds another epicycle to the DM paradigm in the form of a dominant, baryonic disc component, the observed correlations, by which only the sub-dominant, visible-baryons component determines everything, would require an even more involved, three-headed conspiracy. This is not an argument that definitely excludes the molecular-DM-plus-CDM hypothesis, but it does diminish its likelihood.

The above argument poses a difficulty for the double DM hypothesis even before we consider the tidal dwarfs themselves. In addition, the present rotation curve results show that the three dwarfs also satisfy the above correlations. This adds another dimension to the above argument: if we accept that the dwarfs formed in a very different way from that of most other galaxies, and that their matter component mixture is very different, why should they still satisfy the same relations? In the dwarfs' case these would be relations between the visible baryons and the molecular DM, while in general they would be relations between the visible baryons and the combined molecular-plus-cold DM. Of course, this latter part of the argument assumes the robustness of the results and interpretation of Bournaud et al., including their deduced inclinations. It is also based, at the moment, on only the three galaxies discussed here. The argument would clearly benefit from further substantiation, and the examination of more tidal dwarfs. Until then it remains a tentative difficulty for the double DM hypothesis.

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REFERENCES

Angus, G.W. & McGaugh, S.S. 2007, arXiv:0704.0381

Bekenstein, J.D. 2006, Contemporary Physics 47, 387

Bottema, R., Pestaña, J. L. G., Rothberg, B., Sanders, R. H. 2002, AA, 393, 453

Bournaud, F., Duc, P.-A., Brinks,E., Boquien, M., Amram, M., Lisenfeld, U., Koribalski, B.S., Walter, F., Charmandaris, V. 2007, Science, 316, 1166

Brada, R. & Milgrom, M. 2000a ApJ, 541, 556

Brada, R. & Milgrom, M. 2000b ApJ, 531, L21

de Blok, E. & McGaugh, S.S. 1998, ApJ, 508, 132

Elmergreen, B.G. 2007, Science (perspectives), 316, 1132

Gentile, G., Famaey, B., Combes, F., Kroupa, P., Zhao, H.S., & Tiret, O. 2007a, AA, in press, arXiv:0706.1976

Gentile, G., Salucci, P., Klein, U., and Granato, G. L. 2007b MNRAS 375, 199

Malphrus, B.K., Simpson, C.E., Gotesman, S.T., & Hawarden, T.G. 1997, AJ 114, 1427

McGaugh, S.S. 2005, ApJ, 632, 859

McGaugh, S.S. 2006, astro-ph/0606351

Milgrom, M. 1983a, ApJ, 270, 365

Milgrom, M. 1983b, ApJ, 270, 371

Milgrom, M. 2002, New Astron.Rev. 46 741

Milgrom, M. & Sanders, R.H. 2007 ApJ, 658, L17

Pfenniger, D., Combes, F., & Martinet, L. 1994, AA, 285, 79

Sanders, R.H. & McGaugh, S.S. 2002, ARA&A, 40, 263

Wu, X., Zhao, H.S., Famaey, B., Gentile, G., Tiret, O., Combes, F., Angus, G.W., & Robin, A.C. 2007, arXiv:0706.3703v2

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