Mark Huisjes

Accelerations from Molecular Clouds in the Milky Way: *Testing MOND on the ~30 parsec scale?*

Mark Huisjes

Molecular Clouds in the Milky Way

Molecular clouds (MCs) are extremely cold (~10K) and fairly dense (~150 cm^{-3}) regions filled with molecular hydrogen that lead to star formation in spiral arms. Molecular hydrogen is hard to observe directly because it has no dipole moment so usually ^{12}CO is used as a proxy. The results presented here are based on the MC catalogue by Miville-Deschênes et al. (2017, hereafter MD17) which includes 8107 MCs covering the entire Galactic plane. The catalogue by MD17 is in turn based on the ^{12}CO emission survey by Dame et al. (2001) representing two decades worth of CO observations at the CfA 1.2 meter Millimeter-Wave Telescope and including 98% of the ^{12}CO emission observed within b ±5°.

The RAR-like result presented here based on the input data from MD17 and some new kinematic distances is very preliminary. The influence of ordinary tidal distortions, the external field effect and magnetic support are still poorly understood. The ellipticity however is accounted for.

External Field Effect (ExFE)

The observed RAR-like signal is unexpected because these systems are embedded in the external field of the Milky Way with an average strength of $2a_0$. The ExFE is defined here by eq. 60 of Famaey & McGaugh (2012). Most of these MCs, and particularly the ones with low internal accelerations, should be Newtonian or quasi-Newtonian in their observed accelerations but they are not.

This can be seen as a serious problem for MOND field theories with external field effects such as AQUAL and QUMOND. This could also be the result of systematics. Although it is rather odd that a RAR-like signal would result out of all the possibilities. Finally the local external field might be much smaller than what is deduced from the large scale rotation curve proxy. This is possible if there are significant local density perturbations. While most MCs are in or near spiral arms where such perturbations must exist, it is unknown if they are pronounced enough to explain the observations.

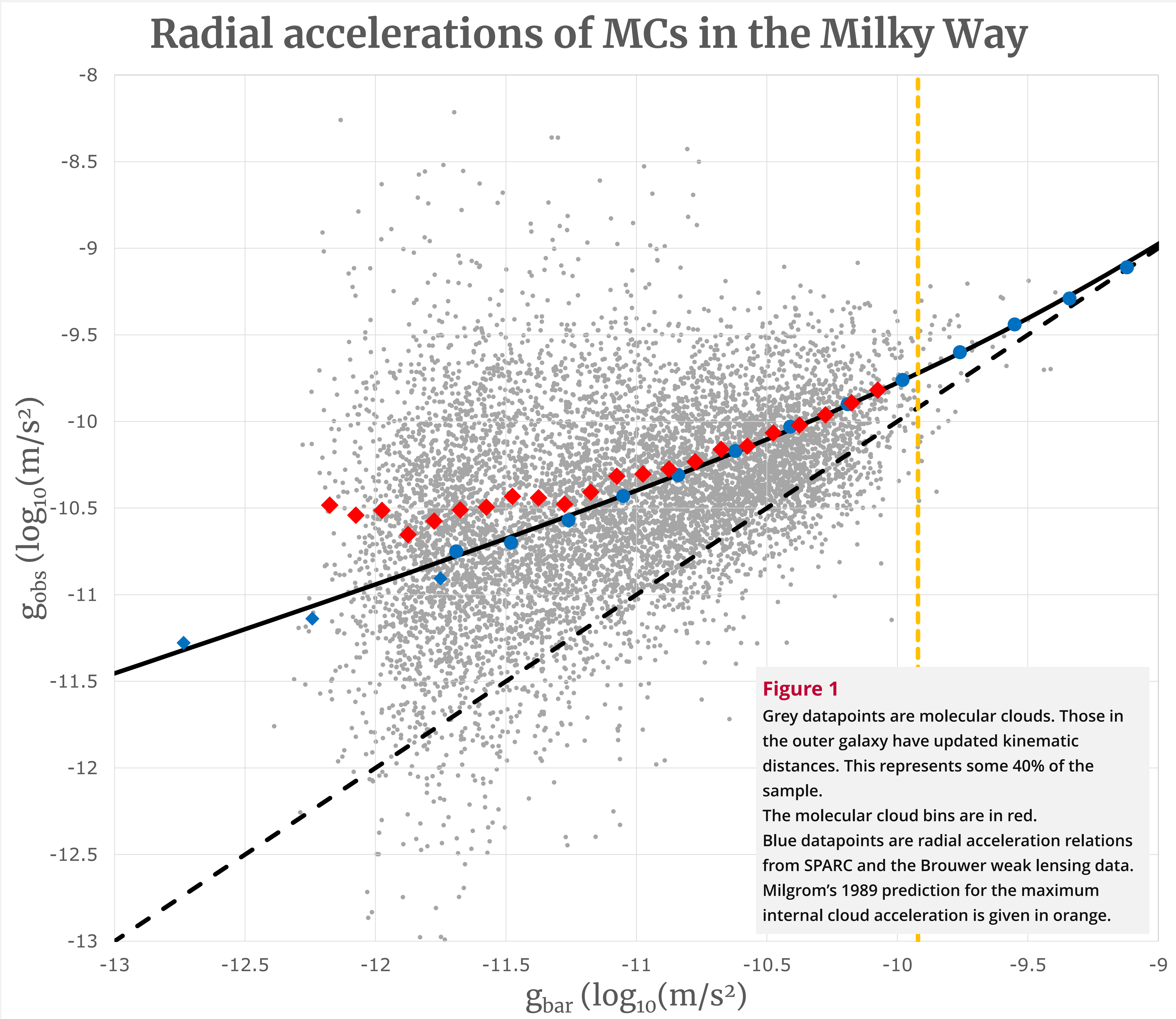

Figure 1
Grey datapoints are molecular clouds. Those in the outer galaxy have updated kinematic distances. This represents some 40% of the sample.
The molecular cloud bins are in red.
Blue datapoints are radial acceleration relations from SPARC and the Brouwer weak lensing data.
Milgrom's 1989 prediction for the maximum internal cloud acceleration is given in orange.

Kinematic Distance Method

Determining the heliocentric distance to an MC is most commonly done using the kinematic distance method (KDM) because they are too far away for parallaxes and other distance indicators require very large amounts of telescope time. The KDM trigonometrically matches the observed radial velocity of a cloud to a particular galactocentric radius using a rotation curve V(r):

$$R_{gal} = R_0 \sin(l) \frac{V(r)}{v_p + V_0 \sin(l)}$$

The results presented here use the slowly declining rotation curve by McGaugh (2019) for the outer galaxy instead of the perfectly flat one by Brand & Blitz (1993) used in MD17. Both curves yield similar results for the inner galaxy. The modern curve by McGaugh is not used in the inner galaxy because its wiggles make the kinematic distance ambiguity much more problematic. The distances to MCs in the outer galaxy are reduced by a factor of up to two. See figure 2 for a comparison of the resultant galactocentric radii.

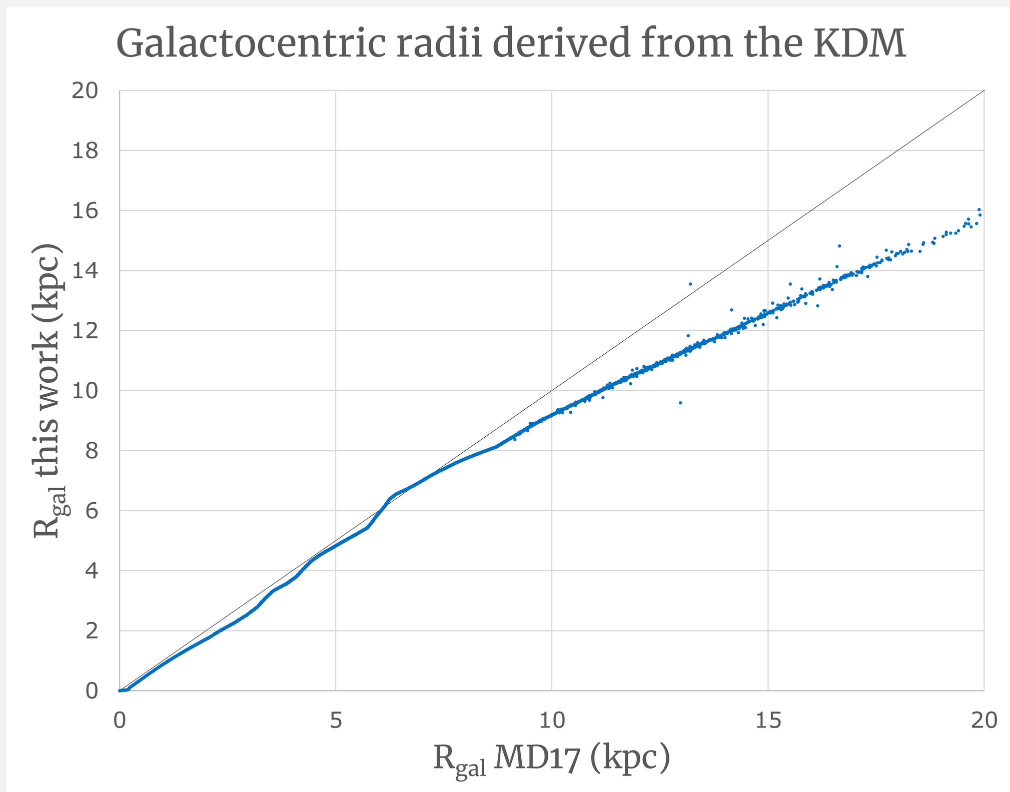

Fig 2
The maximum R_{gal} by MD17 is at 93 kpc. This is reduced to 43 in this work.

Kinematic Distance Ambiguity

In the inner galaxy the KDM using a monotonically increasing rotation curve results in two possible distances due to the ambiguous case of the law of sines. A choice must be made whether a system is at the near or the far distance. This can result in up to an order of magnitude difference in the total molecular hydrogen mass if done poorly. MD17 selects the systems deviating the least from the empirical σ_{los}-R relation and gets a total mass of 1.6 x 10^9 $M_\odot$. The new distances in the outer galaxy reduce this to 1.5 x 10^9 $M_\odot$. In principle the RAR could be used for this too. This will be a topic of further research.

References

Brand, J., & Blitz, L. (1993). The velocity field of the outer Galaxy. *Astronomy & Astrophysics*, *275*, 67–90.

Brouwer, M. M., Oman, K. A., Valentijn, E. A., Bilicki, M., Heymans, C., Hoekstra, H., Napolitano, N. R., Roy, N., Tortora, C., Wright, A. H., Asgari, M., Van Den Busch, J. L., Dvornik, A., Erben, T., Giblin, B., Graham, A. W., Hildebrandt, H., Hopkins, A. M., Kannawadi, A., … Visser, M. (2021). The weak lensing radial acceleration relation: Constraining modified gravity and cold dark matter theories with KiDS-1000. *Astronomy and Astrophysics*, *650*, 1–30. https://doi.org/10.1051/0004-6361/202040108

Dame, T. M., Hartmann, D., & Thaddeus, P. (2001). The Milky Way in Molecular Clouds: A New Complete CO Survey. *The Astrophysical Journal*, *547*(2), 792–813. https://doi.org/10.1086/318388

Famaey, B., & McGaugh, S. S. (2012). Modified newtonian dynamics (MOND): Observational phenomenology and relativistic extensions. *Living Reviews in Relativity*, *15*. https://doi.org/10.12942/lrr-2012-10

McGaugh, S. S., Lelli, F., & Schombert, J. M. (2016). Radial acceleration relation in rotationally supported galaxies. *Physical Review Letters*, *117*(20), 1–6. https://doi.org/10.1103/PhysRevLett.117.201101

McGaugh, S. S. (2019). The Imprint of Spiral Arms on the Galactic Rotation Curve. *The Astrophysical Journal*, *885*(1), 87. https://doi.org/10.3847/1538-4357/ab479b

Milgrom, M. (1989). Concerning the preferred surface density of giant molecular clouds in the Galaxy. *Astronomy & Astrophysics*, *211*, 37–40.

Miville-Deschênes, M.-A., Murray, N., & Lee, E. J. (2016). Physical Properties of Molecular Clouds for the Entire Milky Way Disk. *The Astrophysical Journal*, *834*(1), 57. https://doi.org/10.3847/1538-4357/834/1/57

Contact me at: markhuisjes@hotmail.com