SF2A 2009
M. Heydari-Malayeri, C. Reylé and R. Samadi (eds)

TESTING GRAVITY IN THE MILKY WAY WITH GAIA

Famaey, B.[1] and Bienaymé, O.[1]

Abstract. With the advent of Gaia, it will be possible to design tests of gravity on the scale of the Galaxy. Observations of external galaxies indeed suggest a one-to-one analytic relation between gravity at any radius and the enclosed baryonic mass, a relation summarized by Milgrom's law of modified Newtonian dynamics (MOND). Within its modified gravity interpretation, MOND makes very specific predictions allowing to differentiate it from a spherical halo of dark matter. Here, we show that MOND can be tested with Gaia by measuring dynamically the disk surface density at the solar radius, the radial mass gradient within the disk, or the velocity ellipsoid tilt angle above the Galactic plane at various heights and various Galactocentric radii. However, these tests require an extremely accurate baryonic mass model for the Milky Way.

1 Introduction

The long-term goal of the Gaia mission is to get an accurate estimate of the Galactic gravitational potential by analyzing the motion of several hundreds millions stars up to ~ 15 kpc: the full dataset should be available around 2020. However, when the first releases of data will be available around 2015, it will already be possible to answer crucial questions about the dynamics of our Galaxy. Among them, a currently harshly debated question is whether the missing mass problem is due to the existence of dark matter or to a modification of the gravitational law on galaxy scales. Here, following the work of Bienaymé et al. (2009), we show how large-scale spectroscopic and astrometric surveys in general, and Gaia in particular, could help answer this question.

2 Cold Dark Matter or Modified Newtonian Dynamics?

The concordance cosmological model based on the existence of Cold Dark Matter (CDM) is very successful on large scales. However, the predictions of the model are in contrast with a number of observational facts on galaxy scales. A non-exhaustive list of issues is (i) the predicted overabundance of satellite galaxies; (ii) the prediction of cuspy dark matter halos, whereas observations point toward dark halos with a central constant density core; (iii) the problems to form large enough baryonic disks due to their predicted low angular momentum within simulations; and (iv) the departures from the CDM scenario recently found in tidal dwarf galaxies (e.g., Gentile et al. 2007). In addition to these discrepancies with observations, galaxies also follow tight scaling relations that are hard to explain without much fine-tuning of CDM. For instance, (i) the baryonic Tully-Fisher relation (relating the baryonic mass of a disk galaxy to the fourth power of its circular velocity), whic! h is valid for all disk galaxies with negligible scatter; (ii) the Faber-Jackson relation (relating the luminosity of an elliptical galaxy to the fourth power of its velocity dispersion), valid for elliptical galaxies, and more generally, the fundamental plane for elliptical galaxies; (iii) the universality of the dark and baryonic surface densities of galaxies within one scale-length of the dark halo (Gentile et al. 2009); and (iv) the mass discrepancy-acceleration relation (relating the dark-to-baryonic mass ratio to the gravitational acceleration), which holds for all disk galaxies at any galactocentric radius (McGaugh 2004). This last relation notably involves an acceleration scale $a_0 \sim 10^{-10}$ ms^{-2} whose significance is far from clear. Below this gravitational acceleration, the enclosed dark mass starts to dominate over baryons in galaxies, and this acceleration scale also fixes the slope and zero-point of the Tully-Fisher and Faber-Jackson relations. Final! ly, galactic rotation curves often display obvious features (bumps or wiggles) that are also clearly visible in the stellar or gas distribution ("Renzo's rule"), which is difficult to understand in galaxies dominated by collisionless dark matter.

---

[1] Observatoire Astronomique, Université de Strasbourg, CNRS UMR 7550, F-67000 Strasbourg, France

Table 1. Values predicted from the Besançon MOND model as seen by a Newtonist compared to observations, for the local surface density and the tilt of the velocity ellipsoid.

	Besançon MOND	Observations
$\Sigma_\odot(z = 1.1\,\mathrm{kpc})$	78 $M_\odot/\mathrm{pc}^2$	74 ± 6 $M_\odot/\mathrm{pc}^2$ (Holmberg & Flynn 2004)
Tilt at $z = 1$ kpc	6 degrees	7.3 ± 1.8 degrees (Siebert et al. 2008)

This could thus all point towards a modification of the gravitational law on galaxy scales: for instance, Milgrom (1983) postulated that for gravitational accelerations below a_0, the true gravitational attraction g approaches $(g_N a_0)^{1/2}$ where g_N is the usual Newtonian gravitational field (as calculated from the observed distribution of visible matter). This alternative paradigm is known as modified Newtonian dynamics (MOND), and uncannily explains all the scaling relations mentioned above (but it does not work for galaxy clusters). Such a modification of Newtonian dynamics could come at the classical (non-covariant) level from a modification of either the kinetic part or the gravitational part of the Newtonian action (with usual notations; ϕ_N being the Newtonian gravitational potential):

$$S = \int \frac{1}{2}\rho v^2 d^3x\,dt - \int \left(\rho\phi_N + \frac{|\nabla\phi_N|^2}{8\pi G}\right) d^3x\,dt, \tag{2.1}$$

where modifying the first term is referred to as "modified inertia" and modifying the second term as "modified gravity". Bekenstein & Milgrom (1984) have devised a modified gravity framework in which $|\nabla\phi_N|^2$ is replaced by $a_0^2 F(|\nabla\phi|^2/a_0^2)$ in Eq. 2.1, where $F(y)$ is a free function with defined asymptotic properties reproducing $g = (g_N a_0)^{1/2}$ in the spherically symmetric weak-field limit.

Within this Bekenstein & Milgrom modified gravity interpretation, MOND makes very specific predictions allowing to differentiate it from a spherical halo of dark matter. Here, we outline these predictions, that Gaia and other large-scale surveys could help to test.

3 How Gaia can help

We build these predictions using the free function $F(y)$ of Famaey & Binney (2005) and the MOND Milky Way model of Wu et al. (2008)[1]. This model is based on one of the most realistic possible baryonic mass models of the Milky Way, the Besançon model (Robin et al. 2003).

Once the MOND gravitational potential of the model is known, one can apply the Newtonian Poisson equation to it, in order to find back the density distribution that would have yielded this potential within Newtonian dynamics. In this context, as shown in Bienaymé et al. (2009), MOND predicts a disk of "phantom" dark matter allowing to differentiate it from a Newtonian model with a dark halo
(i) By measuring the force perpendicular to the Galactic plane: at the solar radius, MOND predicts a 60 percent enhancement of the dynamical surface density at 1.1 kpc compared to the baryonic surface density, a value not excluded by current data. The enhancement would become more apparent at large galactic radii where the stellar disk mass density becomes negligible.
(ii) By determining dynamically the scale length of the disk mass density distribution. This scale length is a factor ∼1.25 larger than the scale length of the visible stellar disk if MOND applies. Such test could be applied with existing RAVE data (Zwitter et al. 2008), but the accuracy of available proper motions still limits the possibility to explore the gravitational forces too far from the solar neighbourhood.
(iii) By measuring the velocity ellipsoid tilt angle within the meridional galactic plane. This tilt is different within the two dynamics in the inner part of the Galactic disk. However the tilt of about 6 degrees at z=1 kpc at the solar radius is in agreement with the recent determination of 7.3 ± 1.8 degrees obtained by Siebert et al. (2008). The difference between MOND and a Newtonian model with a spherical halo becomes significant at z=2 kpc.

---

[1] We use the model labelled "MOND $g_{\mathrm{ext}} = 0.1a_0$" in Wu et al (2008), meaning that the modulus of the external gravitational field acting on the Milky Way is chosen to be $a_0/100$

Such easy and quick tests of gravity could be applied with the first releases of future Gaia data. To fix the ideas on the *current* local constraints, the predictions of the Besançon MOND model are compared with the relevant observations in Table 1. Let us however note that these predictions are *extremely* dependent on the baryonic content of the model, so that testing gravity at the scale of the Galaxy heavily relies on star counts, stellar population synthesis, census of the gaseous content (including molecular gas), and inhomogeneities in the baryonic distribution (clusters, gas clouds).

We thank HongSheng Zhao, Xufen Wu, and Dominique Aubert for their contribution to Bienaymé et al. (2009).

References

Bekenstein, J., Milgrom, M., 1984, ApJ, 286, 7

Bienaymé, O., Famaey, B., Wu, X., et al., 2009, A&A, 500, 801

Famaey, B., Binney, J., 2005 MNRAS, 363, 603

Gentile, G., Famaey, B., Combes, F., et al., 2007, A&A, 472, L25

Gentile, G., Famaey, B., Zhao, H.S., Salucci, P., Nature, 461, 627

Holmberg, J., Flynn, C., 2004, MNRAS, 352, 440

McGaugh, S.S., 2004, ApJ, 609, 652

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

Robin, A. C., Reylé, C., Derrière, S., Picaud, S., 2003, A&A, 409, 523

Siebert, A., Bienaymé, O., Binney, J., et al., 2008, MNRAS, 391, 793

Wu, X., Famaey, B., Gentile, G., et al., 2008, MNRAS, 386, 2199

Zwitter, T., Siebert, A., Munari, U., et al., 2008, AJ, 136, 421