Is the Large Magellanic Cloud on a bound orbit ?

-- A robust test of the CDM and MOND potentials of the Milky Way

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Abstract

We compute the Milky Way potential in different Cold Dark Matter (CDM) based models, and compare these with the MOdified Newtonian Dynamics (MOND) framework. We calculate the axis ratio of the potential in various models, and find that isopotentials are less spherical in MOND than in CDM potentials. As an application, we predict the escape velocity as a function of position in the Galaxy. The recently measured high proper motion of the LMC would make the LMC escape from potentials of all CDM models of the MW in the literature. To bind the LMC to the Galaxy in a MOND model, while still being compatible with the RAVE-measured local escape speed at the Sun's position, we show that the MW should move in a mild external field, i.e., a systematic acceleration of less than 1600 km/s per 14 Gyrs with respect to the average frame of the CMB or of all galaxies.

Introduction

A modification of the Newtonian dynamics (MOND) has been suggested as an alternative to the elusive cold dark matter (CDM) models when explaining the galaxy kinematics. In MOND the Newtonian gravitational acceleration g_N is replaced with $g \sim \sqrt{(g_N a_0)}$ when the gravitational acceleration is far smaller than the acceleration constant $a_0 = 1.2\times10^{-10}$ m/s^2, and tightly fits the observations without dark matter in different types of galaxies (Bekenstein & Milgrom 1984). Unlike in CDM, the Strong Equivalence Principle is violated in MOND when considering the External Field (EF) in which a system is embedded. The EF enables stars with zero effective internal energy escape from MOND systems. The order of magnitude of the EF at the position of the Milky Way (MW) is the acceleration endured during a Hubble time in order to attain a peculiar velocity of 600km/s, i.e. $H_0 \times 600$km/s ~ $0.01 a_0$. Hence the modified Poisson equation is

$$-\nabla\cdot[\mu(|g|/a_0)\, g] = 4\pi G\varrho, \qquad g = g_{ext} - \nabla\Phi_{int}\,. \qquad (1)$$

Milky Way Models

MOND: We model the Milky Way in MOND following the Besançon baryons model (Robin et al. 2003) (Fig. 1). The external field is presumably due to the local gravitational attraction of Large Scale Structure, and mainly from the so-called Great Attractor region in the Sun-Galactic Centre direction. The RAVE survey constrains the external field $g_{ext} = 0.01^{+0.02}_{-0.0075} a_0$. We choose values of external field $g_{ext} = 0.01a_0$ and $0.03a_0$.

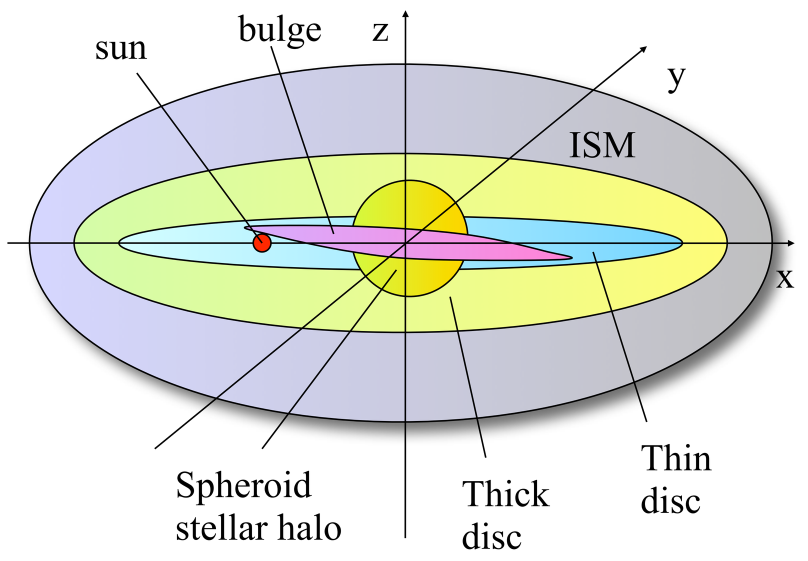


Fig.1 Besançon Milky Way baryons Model: The x-axis is sun-galactic center and z-axis is vertical direction.

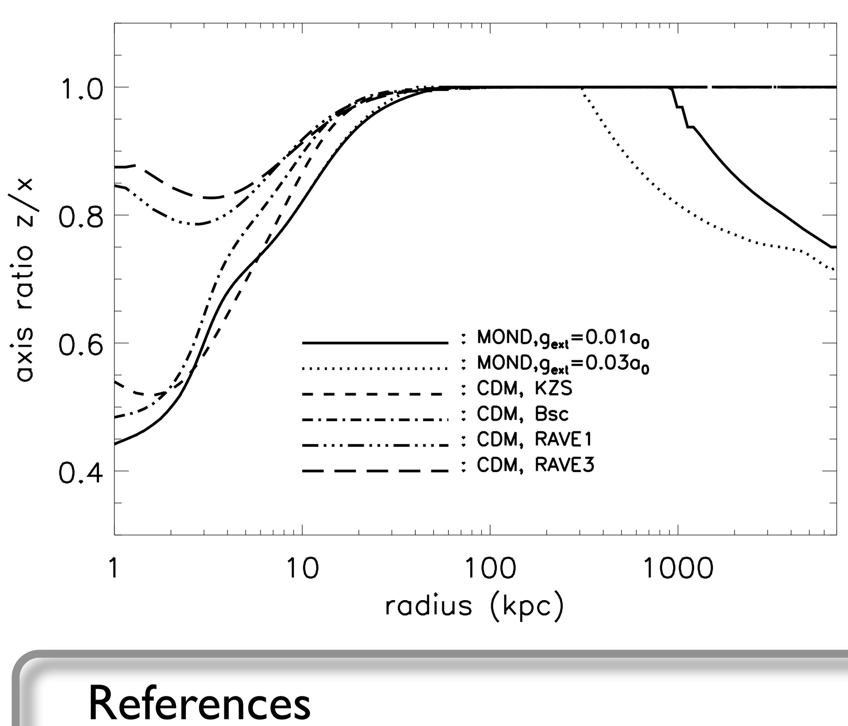
CDM: CDM-based models are far from unique. We limit ourselves to four CDM models here: two based on the work of Klypin, Zhao & Somerville (2002) (KZS and Bsc models), and two based on the recent work of the RAVE collaboration on the local escape speed from the Solar Neighbourhood (Smith et al. 2007) (RAVE1 and RAVE3 models).

Potentials

The solution of equation (1) at infinity is

$$\Phi_{int}^{\infty} = -\,GM/\{\mu(g_{ext}/a_0)\sqrt{[(1+\Delta)(y^2+z^2)+x^2]}\}$$

here Δ is a dilaton factor ranging in [0,1]. Δ=0 is Newtonian limit and Δ=1 is deep MOND limit. The the external field ($0.01a_0$ and $0.03a_0$) in the x-direction actually makes the MOND potential oblate again at very large radii, asymptoting to a z-x axis ratio of 0.7 at infinity (Fig. 2a).



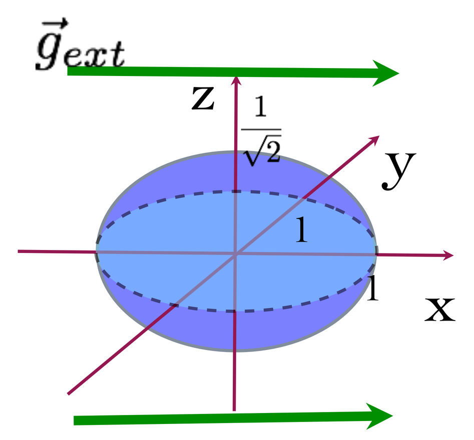


Fig2. Left panel: Potential axis ratio. Right panel: MOND Potential at infinity, prolate along EF (weak field) direction.

Phantom dark matter

Once the MOND potential is known, one can use the Newtonian Poisson equation to derive the corresponding density of matter that would be needed in the Newtonian context. Cones of ***negative*** phantom dark matter densities (dashed line contours in Fig.3) perpendicular to the external field direction are predicted at 600 kpc, when the internal and external gravitational fields are of the same order of magnitude. We could expect to detect such negative dark matter effect through weak gravitational lensing : the negative dark matter would produce a negative convergence $\varkappa$.

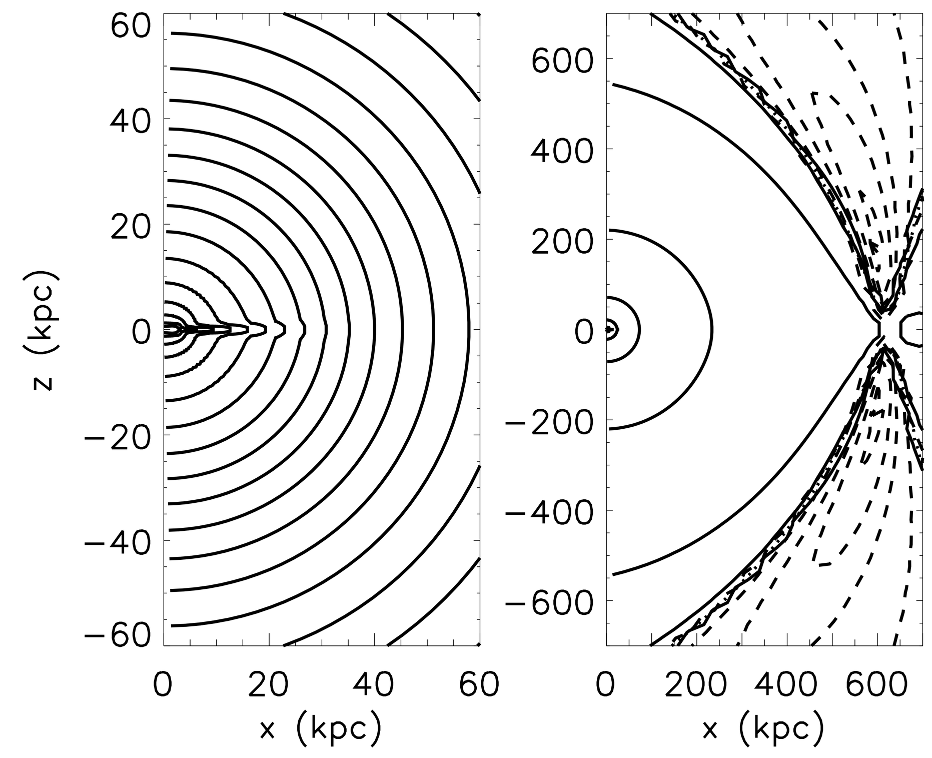


Fig.3 Isodensity of phantom dark matter in a MOND Milky Way embedded in an external field of $0.01a_0$. Left panel is on small scale showing phantom dark matter distribution follows the baryons, while right panel is on larger scale. The solid and dashed contours are isodensity for positive and negative density respectively, and the dotted line is the watershed with zero-density.

Escape velocity of the LMC

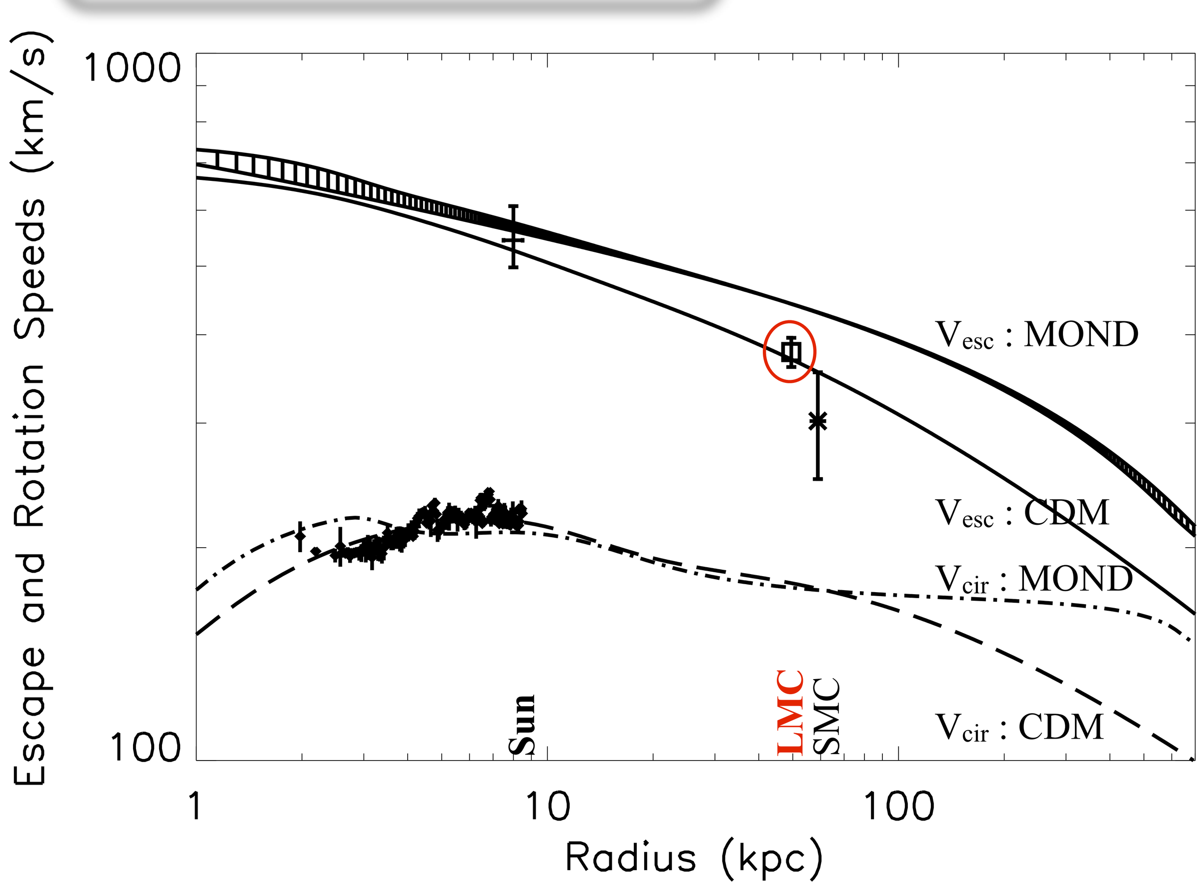


Fig.4 The solid lines are the escape and circular speeds for the KZS B1 model (Upper and Bottom solid lines: escape velocity and circular speed of the KZS B1 model). The dot-dashed lines are the MOND circular speed (with low external field of $0.01a_0$), and the shaded area is the escape velocity in MOND. Diamonds with error bars are the observed circular velocity (Clemens 1985) and the error bar at 8.0±0.5 kpc is the escape velocity in the solar neighbourhood measured from the RAVE survey. The square and star with error bars are the newly mesaured LMC and SMC speed (Kallivayalil et al. 2006a,b). The other three CDM models have the similar results.

The Large Magellanic Cloud is the nearest satellite of the Milky Way. The newly measured 3D velocity pointed out that it is difficult for the LMC to be a bound satellite with CDM-based halos. In contrast, the MOND potential with an external field of $0.01a_0$ is significantly deeper. Therefore, LMC is undoubtedly captured by the Galaxy in this MOND potential.

Predictions for HVSs and SDSS Survey

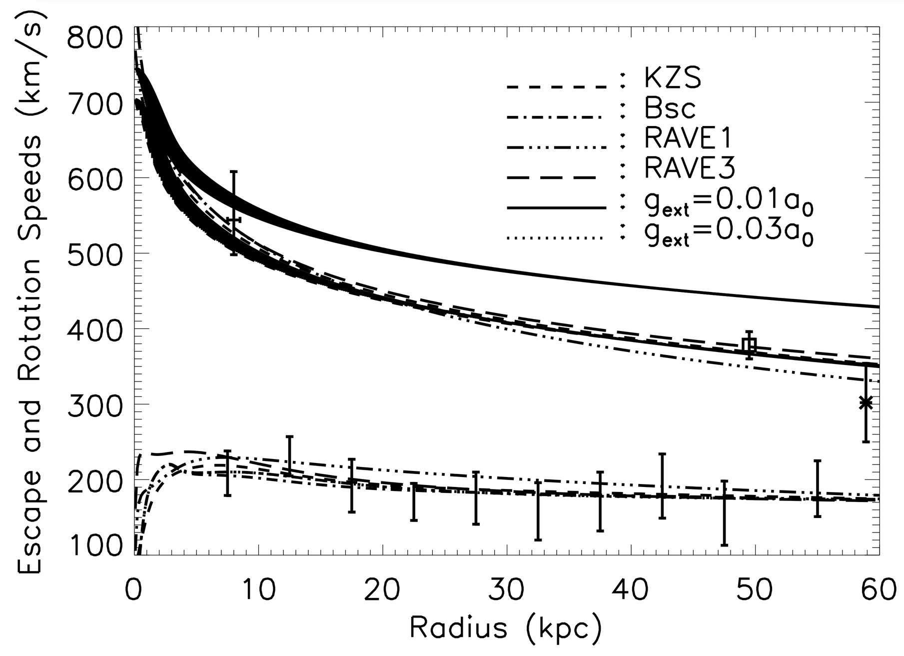


Fig. 5 : The circular and escape velocities in the Galaxy calculated in the different models. The two shaded areas are the escape velocity in MOND within an external field of $0.01a_0$ and $0.03a_0$. The other upper curves are the CDM predictions for the escape velocity, as shown in the label. The error bar at 7.5-8.5kpc is the RAVE escape velocity. The data below are the circular speed measured by Xue et al. (2008) from SDSS field stars data.

The circular and escape velocity in the MOND model with an external field of $0.03a_0$ are extremely similar to CDM. Consequently, this MOND potential effectively mimics the NFW potential.

In recent years several Hyper Velocity Stars have been observed at large distances in the Galactic halo (up to ~100 kpc). Observations of any incoming HVSs would rule out the CDM models and the MOND model with an external field of $0.03a_0$.

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Conclusions

1. Isopotentials are more spherical in CDM ;
2. The phantom dark matter densities predicted by MOND can be negative ;
3. The LMC is about to escape in CDM;
4. The 3D velocity of LMC and HVSs could constrain the Milky Way models.

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