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THE SAGITTARIUS TIDAL STREAM AS A GRAVITATIONNAL EXPERIMENT IN THE MILKY WAY

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Abstract. Modified Newtonian Dynamics (MOND or Milgromian dynamics) gives a successful description of many galaxy properties that are hard to understand in the classical framework. The rotation curves of spiral galaxies are, for instance, perfectly reproduced and understood within this framework. Nevertheless, rotation curves only trace the potential in the galactic plane, and it is thus useful to test the shape of the potential outside the plane. Here we use the Sagittarius tidal stream as a gravitational experiment in the Milky Way, in order to check whether MOND can explain both its characteristics and those of the remnant dwarf spheroidal galaxy progenitor. We show that a MOND model of the Sagittarius stream can both perfectly reproduce the observed positions of stars in the stream, and even more strikingly, perfectly reproduce the observed properties of the remnant. Nevertheless, this first model does not reproduce well the observed radial velocities, which could be a signature of a rotating component in the progenitor or of the presence of a massive hot gaseous halo around the Milky Way.

Keywords: Modified gravity, Sagittarius, galaxy, stream

1 Introduction

Some discrepancies appear at galactic scales between the observations and the predictions from ΛCDM simulations. Indeed, in rotationally supported galaxies the asymptotic velocity is related to the baryonic mass via the baryonic Tully-Fisher, which has intrinsically negligible scatter (McGaugh 2012), the shape of rotation curves in dark matter dominated galaxies is not correlated with V_{max} but rather with the baryonic surface density (Famaey & McGaugh 2012; Oman et al. 2015), and many observations indicate that dynamical friction is not as efficient as expected in ΛCDM (Kroupa 2015). Galaxy merger simulations such as those of the Antenna galaxies can produce long tidal tails as observed only if DM halos are truncated to almost one-tenth of the actual virial radius.

These problems disappear if we consider that gravity is effectively modified on galaxy scales as proposed by Milgrom (1983), a paradigm known as Modified Newtonian Dynamics (MOND) where the gravitational law is effectively modified in the weak acceleration regime, typically when the acceleration falls under a_0, a new constant with the dimension of acceleration (of order 10^{-10} m.s^{-2}). However it is currently impossible to explain the observations at the cosmological scales without adding some sort of DM, or at least a new degree of freedom behaving as a collisionless dust fluid on these scales.

In galaxies, the shape of the rotation curve gives us information about the potential only in the galactic plane, and the best tracers of the potential outside this plane are the tidal streams. They are the consequences of the stripping of satellites galaxies while they orbit the host galaxy. The most studied of them is the Sagittarius Stream in our own Milky Way galaxy (Ibata et al. 1994). The presence of a remnant progenitor dwarf spheroidal galaxy (Sgr dSph) for this stream is the source of a lot of information about the initial conditions of this satellite and on the potential. This stream has been heavily studied through N-body simulations (Law et al. 2005; Law & Majewski 2010) or by various analytical models, mostly ignoring dynamical friction, by, e.g., spraying particles at Lagrange points at different time steps (Varghese et al. 2011; Küpper et al. 2012). However, a full study of

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streams in a modified gravity framework is still lacking. The only study dates back to Read & Moore (2005) who concluded that the orbit of a single point mass was very similar to that of a point mass in a spherical DM halo.

In Sec.2 we present a brief overview of how we modelled the initial satellite galaxy and the MW in MOND. The results of our simulations are developed in Sec.3 and our conclusions and perspectives are treated in Sec.4.

2 Constructing the model

2.1 The QuMOND formulation

The classical Newtonian action for a set of particles generated by the matter density distribution ρ generating the Newtonian potential Φ_N is given by :

$$S_N = S_{kin} + S_{in} + S_{grav} = \int \frac{\rho \mathbf{v}^2}{2} d^3x\,dt - \int \rho \Phi_N d^3x\,dt - \int \frac{|\nabla \Phi_N|^2}{8\pi G} d^3x\,dt \tag{2.1}$$

The equations of motion and the Poisson equation result through the variation of this action w.r.t. the coordinates or to the potential itself.

Proposed by Milgrom (2010), QuMOND is a non-relativistic formulation of the MONDian paradigm where the matter action is unmodified but where the gravitational action (the third term of equation 2.1) is generalized by introducing an auxiliary acceleration field (Milgrom 2010; Famaey & McGaugh 2012). Finally the MONDian potential Φ can be computed by the MONDian Poisson equation :

$$\nabla^2 \Phi = 4\pi G(\rho_b + \rho_{ph}) \tag{2.2}$$

where ρ_b is the baryonic matter density that generates the Newtonian potential Φ_N with the classical Newtonian Poisson equation $\rho_b = (\nabla^2 \Phi_N)/(4\pi G)$ and ρ_{ph} is the phantom dark matter (PDM) density. The PDM is an effective matter density and can be seen as a mathematical ansatz that is useful for interpreting MOND in the dark matter language. This density results directly from the baryonic density :

$$\rho_{ph} = \nabla \left[\tilde{\nu} \left(\frac{|\nabla \Phi_N|}{a_0} \right) \nabla \Phi_N \right] \tag{2.3}$$

$\tilde{\nu}(y)$ is the interpolation ν-function and $\tilde{\nu}(y) \to 0$ when $y \gg 1$ (Newtonian regime) and $\tilde{\nu}(y) \to y^{-1/2} - 1$ when $y \ll 1$ (Deep MOND regime) that gives the variation of the potential beside the Newtonian potential over the acceleration. In our work we use 3 different ν-functions :

- the simple ν-function defined by Famaey & Binney (2005) : $\tilde{\nu}(y) = \frac{1+(1+4y^{-1})^{1/2}}{2} - 1$
- the standard ν-function : $\tilde{\nu}(y) = \left[\frac{1+(1+4y^{-2})^{1/2}}{2}\right]^{1/2} - 1$
- the exponential ν-function : $\tilde{\nu}(y) = (1 - e^{-y^2})^{-1/4} + (1 - \frac{1}{4})e^{-y^2} - 1$

With this formulation it is very easy to determine the potential by solving twice the Poisson equation and once the equation 2.3. In this way, all grid-based N-body methods can be adapted to do MONDian simulations. We use hereafter the AMR code Phantom-Of-Ramses (POR) developed by Lüghausen et al. (2014) based on the code Ramses (Guillet & Teyssier 2011).

2.2 Modelling the Milky Way

We assume that the purely baryonic Milky Way is well modelled by the first model of Dehnen & Binney (1998) without the dark halo component. This model features a double exponential stellar disk of $3.52 \times 10^{10} M\odot$ to fit the thin and the thick component with a scale length of 2 kpc and the two scales heights of 0.3 and 1 kpc, respectively. The bulge and the interstellar medium components have respectively a mass of $0.518 \times 10^{10} M\odot$ and $1.69 \times 10^{10} M\odot$.

The host galaxy has a direct importance on the internal dynamic of the dwarf accreted galaxy. Indeed, MOND is a non-linear theory which breaks the strong equivalence principle (SEP), this means that the external field effect (EFE), produced by the host galaxy, affects the internal dynamics of the dwarf. The EFE effectively truncates the satellite's PDM halo therewith making it more susceptible to disruption.

2.3 Modelling the Sagittarius galaxy

The Sagittarius galaxy is a dSph whose observed density is well modelled by a King profile (see Binney & Tremaine 2008). To be self-consistent in MONDian dynamics, we used a MONDified King model where the density $\rho_{b,\,King}$ can be calculated by the Eq.2.4 with ψ being the MONDian binding potential.

$$\rho_{b,\,King} \propto e^{\psi/\sigma} erf\left(\frac{\sqrt{\psi}}{\sigma}\right) - \sqrt{\frac{4\psi}{\pi\sigma^2}}\left(1+\frac{2\psi}{3\sigma^2}\right) \tag{2.4}$$

The MONDian binding potential ψ is determined by the Newtonian binding potential ψ_N and the density by Eq.2.5, since a King profile has spherical symmetry.

$$\begin{aligned} \nabla^2\psi_N &= -4\,\pi\,G\,\rho_{b,\,King} \\ \nabla\psi &= \nu\left(\frac{\nabla\psi_N}{a_0}\right)\nabla\psi_N \end{aligned} \tag{2.5}$$

We then integrate Eq.2.4 inside-out to get a stable King profile in MOND. The velocities are drawn from the corresponding phase-space distribution function, using the MOND potential to determine the energy.

We assume that the current position and velocity of the remnant of the Sgr dSph is the same as in Law & Majewski (2010) : $(l,\,b) = (5.6, -14.2)$ (Majewski et al. 2003), at a distance of 28 kpc (McConnachie 2012), a radial velocity of $v_{rad} = 171$ km.s^{-1} and an apparent proper motion of $(\mu_l\,\cos b,\,\mu_b) = (-2.16,\,1.73)$ mas. yr^{-1}. The initial position is determined by launching the galaxy backward for about 4 Gyr.

3 Results

We want the features of the remnant at the end of the simulations to be similar to those observed. Our best initial model which can match the current observation is a King sphere with a mass $M_{b,\,0Gyr} = 5.8.10^7$ M$_\odot$ and a half-light radius $r_h = 0.41$kpc which gives after 4 Gyr a baryonic mass of $M_{b,\,4Gyr} \sim 2.5.10^7$ M$_\odot$, a half light radius $r_{h,\,4Gyr} = 0.6$ kpc and a velocity dispersion $\sigma_{rad,\,4Gyr} = 11$ km/s in agreement with the observation of Majewski et al. (2003) (here after called M03).

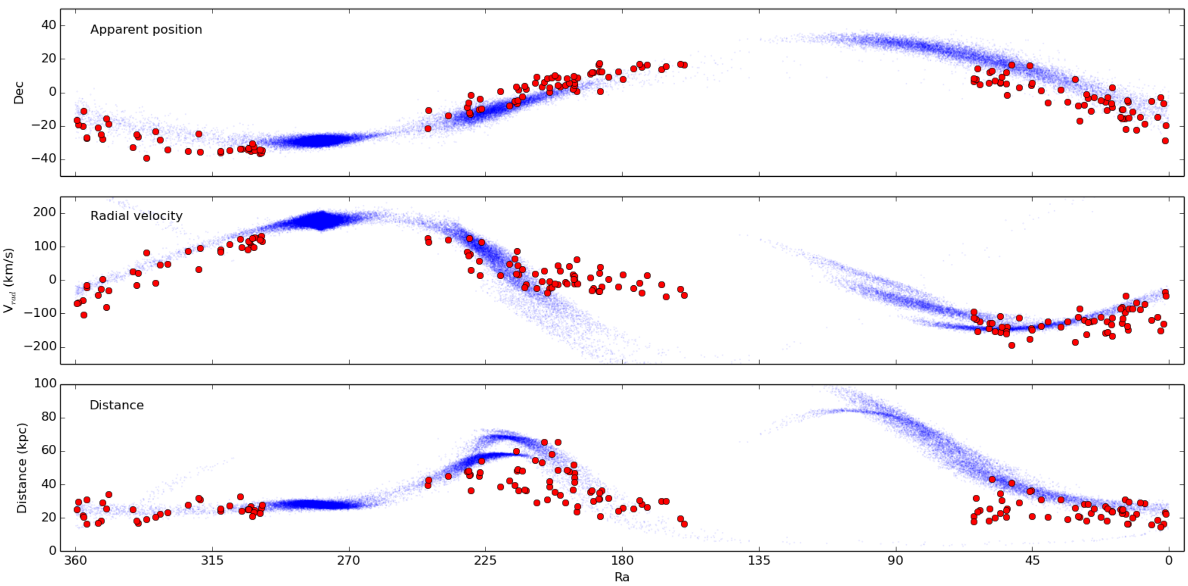

Fig. 1. Apparent position, radial velocity and distances of the stellar particles of our simulation in blue and stars from M03 in red.

On Figure 1, the apparent position of the particles of our simulation fits well the observed positions of the stars from the Sagittarius stream selected by M03. However, the amplitude of the radial velocity between RA=160-240 is more pronounced in the simulations than in the observations.

4 Conclusions and perspectives

We showed that a MOND model of the Sagittarius stream can both perfectly reproduce the observed positions of stars in the stream, and even more strikingly, perfectly reproduce the observed properties of the remnant. Nevertheless, this first model shows interesting deviations from the observed radial velocities between RA=160-240.

This behaviour of the radial velocities could actually be the signature of a rotating progenitor with $V_{flat} \simeq 33$ km.s^{-1}. Indeed, the angular momentum of a rotating dwarf spiral galaxy decreases during the accretion by the loss of stars, thus can produce a dSph remnant after 4 Gyr. Since the remnant is not rotating, the rotating material must either be in a disk, or MOND gravity must have a slow-down effect on the rotation.

A lack of baryonic matter can also explain the radial velocity in our simulation. Indeed, assuming a universal baryon fraction of 0.165 (Komatsu et al. 2011), the predicted baryonic mass of the MW is of $1.65 - 3.3 \times 10^{11}$ $M_\odot$, well above the observed baryonic mass ($\sim 0.6 \times 10^{10} M_\odot$). This lack of matter could be explain by a hot gaseous halo (T$\sim 10^6$ K) with a mass of about 10^{11} $M_\odot$, which could be non-spherically symmetric, and needs to be included in our future works.

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