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THE JEANS MODELING OF THE MILKY WAY GALAXY

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Abstract. In this work we investigate the predictions of Newtonian dynamics and the MOND theory related to the Milky Way galaxy using the Jeans equation. We used the measurements of the radial velocities of the blue horizontal branch (BHB) halo stars to test the predictions of Newtonian gravity and to also extend our study to different MOND models, taking orbital anisotropies that we calculate into account. The halo stars of the Galaxy were used as a tracer of the Galaxy's gravitational potential. The Jeans equation was calculated for both the Newtonian and the MOND approaches. We assumed spherical symmetry and calculated the Jeans equation by taking orbital anisotropies into account. Circular velocities for both approaches were also analyzed. We solved the Jeans equation in spherical approximation and confirm that the Newtonian model without dark matter cannot fit the observed velocity dispersion profile and that the truncated flat model with dark matter can provide a good fit to the observed velocity dispersion. For the MOND models, from the Jeans modeling we found that three models ("simple", "standard" and Zhao, 2007) can provide a fit to the data without significant anisotropies whereas the "toy" model needs anisotropies to obtain the same result.

1. INTRODUCTION

The mass profile and the problem of dark matter in the Milky Way galaxy are frequently discussed in the literature (see e.g., Gnedin et al. 2010). Since the tracers of rotation of the disk, both stars and gas, extend out to 20 kpc, various alternatives have been sought. These alternatives are based on solving of the Jeans equation, in which one models the profile of radial velocity dispersion of the tracers of the mass of the Galaxy. Recently, Brown et al. (2010) (hereafter Bro10) have used their sample of 910 distant halo stars from the Hypervelocity star survey to derive the velocity dispersion profile of the Galaxy. Their sample includes 74% of evolved BHB stars and 26% blue stagglers, and it contains twice as many objects beyond ~ 50 kpc as previous surveys. They find that the Milky Way shows a mean decline in radial velocity dispersion of -0.38 ± 0.12 km s^{-1}kpc^{-1} over $15 < R < 75$ kpc. Xue et al. (2008) (hereafter Xue08) derived new constraints on the mass of the dark matter halo using a sample of 2401 carefully selected BHB stars taken from SDSS DR6. The results of Xue08 were used in the paper by McGaugh (2008), who modeled the outer rotation curve of the Milky Way using MOND. He finds that MOND (Milgrom 1983) naturally provided good match to the rotation curve and that dark matter is not needed within this approach. On the other hand, the results of Bro10 were used in the paper by Gnedin et al. (2010) to find that the total mass of the Milky Way within 80 kpc is $6.9^{+3.0}_{-1.2} \times 10^{11} M_{\odot}$ and that the observed approximately constant velocity dispersion profile requires a massive and extended dark halo. One important aspect of modeling the total mass of some galaxy (and of course, the Galaxy, as well) is the problem of anisotropies in the motion of the chosen tracers because of the well-known mass-orbital anisotropy degeneracy. In the present work we use standard statistical approach, from the observed radial velocities of BHB stars in our sample to calculate radial velocity dispersion but also skewness and kurtosis, which provide information about anisotropies of the motion of the tracers.

2. OBSERVATIONAL DATA

2. 1. HALO STARS OF THE MILKY WAY

We used the same sample of stars as Xue08 along with those in Bro10 not already included from Xue08. We want to secure more stars in the outer region of the Milky Way (outside 60 kpc). In total we have 2557 stars that are found out to 85 kpc: 2416 from Xue08 and 141 from Bro10. All these stars were selected to satisfy the following criteria: i) they must have $|z| > 4$ kpc in order to exclude thick-disk stars; ii) radial velocity error is less than 30 km s^{-1}, and iii) they are all BHB stars. (The likelihood of being BHB star is $f = 1$ in Bro10, Xue08 contains only BHB stars.)

The kinematics of the Milky Way is given in Fig. 1. in Samurović & Lalović (2011, hereafter SL11): it was shown that the profile of the velocity dispersion remains approximately constant (within the error bars) throughout the whole observed region. The skewness parameter is either consistent with zero or is moderately positive and the kurtotic parameter, apart from one point at 25 kpc, is consistent with zero and moderately negative. The future surveys will narrow down the error bars in the estimates thus imposing stronger constraints on the kinematics of the Milky Way galaxy in its outer regions.

Since in the Jeans equation that we solve (see below) there is also a rotational term, we calculated the rotation of BHB stars in the sample. The procedure consists of fitting a sine-curve to the velocities as the function of the position angle Θ:

$$v_{\rm r} = V_{\rm sys} + A_{\rm rot} \sin(\Theta), \tag{1}$$

where $V_{\rm sys}$ is the systemic velocity and $A_{\rm rot}$ rotation amplitude and the fitting is done in four bins with approximately the same number of stars per bin. The position angle Θ is measured in the plane of the Milky Way between the direction towards the Sun and the projection of the star's position onto the Galactic plane. It ranges between -180 and 180 degrees and is measured positive in the clockwise direction as seen from the north Galactic pole. We calculated the rotation amplitude for 1000 Monte Carlo realizations by keeping the positions of our original dataset while permuting the velocities. Thus, we obtained the fraction f' (prime in the exponent avoids confusion with the parameter f mentioned above) of Monte Carlo runs for which a rotation amplitude is larger than the observed one. We showed that the rotation amplitude is small and consistent with zero in the first three bins, whereas in the last, wide bin ($28 < r < 85$ kpc) there is an indication of the non-zero rotational signal.

We solve the spherically symmetric Jeans equation,

$$\frac{\mathrm{d}\sigma_r^2}{\mathrm{d}r} + \sigma_r^2 \frac{(2\beta_* + \alpha)}{r} = a_{N;M} + \frac{v_{\rm rot}^2}{r}, \tag{2}$$

in both the Newtonian and the MOND approaches and $a_{N;M}$ is an acceleration term, that is equal to $a_N = -\frac{GM(r)}{r^2}$ for Newtonian ('N') models and for MOND ('M') models $a_M \mu(a_M/a_0) = a_N$ (see below for details regarding function μ), and σ_r is the radial stellar velocity dispersion, $\alpha = \mathrm{d}\ln\rho/\mathrm{d}\ln r$ is the slope of tracer density ρ and is taken to be $\alpha = -4$ (see Gnedin et al. 2010 for details). We also make use of the following equation for the acceleration: $\frac{d\Phi}{dr} = \frac{GM(r)}{r^2} = \frac{V_c^2}{r}$, where V_c is the circular velocity. As shown above the rotation speed $v_{\rm rot}$ of BHB stars is either consistent with zero or is very small and will be neglected in all modeling below. The nonspherical nature of the stellar velocity dispersion is described by the β_* parameter: $\beta_* = 1 - \frac{\overline{v_\theta^2}}{\sigma_r^2}$, where $\overline{v_\theta^2} = \overline{v_\theta}^2 + \sigma_\theta^2$. In both the Newtonian and the MOND approaches we use the following components of the mass: the bulge with total mass $M_{\rm bulge} = 1.5 \times 10^{10} M_\odot$ (Xue08), the stellar disk with the total mass $M_{\rm stdisk} = 5 \times 10^{10} M_\odot$ (Xue08), and the gas disk with the total mass $M_{\rm gasdisk} = 1.18 \times 10^{10} M_\odot$ (McGaugh 2008). The total disk mass is then $M_{\rm disk} = M_{\rm stdisk} + M_{\rm gasdisk} = 6.18 \times 10^{10} M_\odot$. In the Newtonian model we add a dark halo, and in the MOND model no additional matter is added in an attempt to fit the velocity dispersion.

2. 2. NEWTONIAN MODELS

In the Newtonian models without dark matter, we adopted the form of the total potential (see Xue08), $\Phi_{\rm tot}(r) = \Phi_{\rm disk}(r) + \Phi_{\rm bulge}(r)$. In the Newtonian models with dark matter we add to the given relation $\Phi_{\rm DM}(r)$ for the truncated flat model. The results of solving Eq. 2 using the aforementioned assumptions are given in Fig. 3 of SL11: visible baryonic mass alone cannot explain the kinematics of the external regions of the Milky Way. Using the measured anisotropies, one finds that a significant amount of additional (dark) matter is needed to obtain a fit to the observed velocity dispersion.

2. 3. MOND MODELS

The MOND theory (Milgrom 1983) is widely used when one models rotation curves of the Milky Way and other spiral galaxies. We solved the nonrotating Jeans equation, again in the spherical approximation, noting that the MOND theory is not insensitive to the mass-orbital anisotropy degeneracy, thus taking the measured orbital anisotropies into account. The Newtonian acceleration is given as $a_N = a\mu(a/a_0)$, where a is the MOND acceleration; here, $\mu(x)$ is the MOND interpolating function, with $x \equiv a/a_0$, and a universal constant $a_0 = 1.35^{+0.28}_{-0.42} \times 10^{-8}$ cm s^{-2}. Thus, for $a \gg a_0$ the interpolation function $\mu(a/a_0) \approx 1$ leads to the Newtonian expression for the acceleration and for $a \ll a_0$ one has $\mu = a/a_0$.

We applied several different MOND approaches: the "simple" MOND formula from Famaey & Binney (2005), the "standard" formula (Sanders & McGaugh 2002), the Bekenstein's "toy" model (Bekenstein 2004) and the Zhao (2007) model. For the details regarding the expressions for $\mu(x)$ and V_c please refer to SL11. We solved the Jeans equation for all the MOND models assuming only visible baryonic mass and orbital anisotropies mentioned earlier, and the results are given in SL11. We stress that there are no free parameters in the models. "Simple", "standard", and Zhao models provide satisfactory fits of the observed velocity dispersion assuming isotropic orbits and the existence of visible baryonic matter alone, whereas Bekenstein's "toy" would need radial anisotropies.

3. CONCLUSIONS

We used a sample of 2557 BHB stars that extend out to 85 kpc to investigate the kinematics of the Milky Way halo. We determined radial velocity dispersions, skewness, and kurtosis parameters and solved the Jeans equation taking orbital anisotropies into account. We found that the profile of the radial velocity dispersion is approximately constant throughout the whole Galaxy with $\sigma_r \approx 100$ km s^{-1}. We investigated the rotation of BHB halo stars and found that the rotation is negligible within a radius ~ 30 kpc and that beyond ~ 30 kpc the rotation amplitude changes from zero, although it remains very low (-8.39 ± 4.88 km s^{-1}). In our Jeans models, we therefore neglected the rotation. We solved the nonrotating Jeans equation in the spherical approximation in both the Newtonian and the MOND approaches. We recovered the well-known result that the kinematics of the Milky Way cannot be fitted without the additional (dark) matter. We tested the truncated flat model and found that it provides a good fit of the observed velocity dispersion, which implies a significant amount of dark matter in the Newtonian approach. We tested four MOND models: "simple", "standard", and Zhao (2007) models provide satisfactory fits of the observed velocity dispersion assuming isotropic orbits and the existence of visible baryonic matter alone, whereas Bekenstein's "toy" would need radial anisotropies for a satisfactory fit. We also tested the circular velocity curves for all the models: the "simple" and Zhao MOND models (which belong to the same family of models) provide the best fit without introducing anisotropies (although some radial anisotropies appear to be necessary in the innermost region), whereas other MOND models would need radial (the "toy" model) and tangential (the "standard" model) anisotropies in their outer parts. It is therefore worth noting that all four MOND models should be taken into account in the studies of galactic dynamics.

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