

ARE MILKY-WAY DWARF-SPHEROIDAL GALAXIES DARK-MATTER FREE?

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Abstract. We have found that the high velocity dispersions of dwarf spheroidal galaxies (dSphs) can be well explained by Milky Way (MW) tidal shocks, which reproduce precisely the gravitational acceleration previously attributed to dark matter (DM). Here we summarize the main results of Hammer et al. (2019) who studied the main scaling relations of dSphs and show how dark-matter free galaxies in departure from equilibrium reproduce them well, while they appear to be challenging for the DM model. These results are consistent with our most recent knowledge about dSph past histories, including their orbits, their past star formation history and their progenitors, which are likely tiny dwarf irregular galaxies.

Keywords: cosmology, dark matter, dwarf galaxies, the Milky Way

1 Introduction

DSphs (including ultra-faint dwarfs, UFDs) in the Milky Way halo are by far the smallest galaxies that can be detected and studied. They are believed to contain large amounts of DM, which fraction is generally assumed to increase with decreasing luminosity or stellar mass (Strigari et al. 2008; Walker et al. 2009; Wolf et al. 2010). The existence of DM has been widely accepted since the discovery of the HI-extended and flat rotation curves in giant spirals (Bosma 1978). The extent of the DM paradigm towards the dwarf galaxy regime has been initiated by Aaronson (1983) on the basis of the too large velocity dispersion of the Draco stars. This pioneering result was only based on 3 stars in Draco, though it has been confirmed by major works that have identified new dwarfs, measured their distances, and performed deep photometry and high resolution spectroscopy of their individual stars. During the last 35 years these long term works have provided robust measurements for several tens of MW dSphs (Muñoz et al. 2018; Fritz et al. 2018, and references therein).

The scaling relations between the visible luminosity, the half light radius, the velocity dispersion and the MW distance can be established for 24 dSphs possessing sufficiently robust measurements. Three dSphs (Sagittarius, Crater II and Bootes I) are clearly outliers in these relations, which leads to a sample of 21 dSphs. Analyzing these data, Hammer et al. (2019) demonstrated that the MW gravitation through tidal shocks can fully account for the dSph kinematics. DM estimates (Walker et al. 2009; Wolf et al. 2010) are based on only the projected mass density along the line-of-sight. Hammer et al. (2019, see their Fig. 1) found that this quantity is highly anti-correlated with the MW distance, a property that cannot be reproduced by DM-dominated models. It is however naturally expected if dSphs are tidally shocked during their first passage into the MW halo.

2 DSph progenitors: A first infall of gas-rich dwarfs in the MW?

GAIA DR2 is revolutionizing our knowledge of the MW dSphs orbits in a two-fold way:

1. It has considerably improved our knowledge of the MW mass distribution up to 20-50 kpc, by establishing a more accurate rotation curve (Eilers et al. 2019; Mróz et al. 2019), and by providing better constraints on the Globular Cluster motions (Eadie & Jurić 2019) and on the estimates of the escape velocity (Deason et al. 2019). These studies provide MW masses ranging from 0.7 to $1 \times 10^{12} M_{\odot}$ (see however Grand et al.

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2019 for a slightly higher value), and all of them seem to exclude larger masses. Fig. 1 shows the different rotation curves and mass distributions of the MW, including the most recent ones (Eilers et al. 2019; Mróz et al. 2019) and the (former) high-mass models (McMillan 2017; Irrgang et al. 2013, with total mass from 1.37 to more than $1.9 \times 10^{12} M_{\odot}$) adopted by Gaia Collaboration et al. (2018) during the release of dSph proper motions. Top panels of Fig. 1 show that high mass models lead to velocities (red and magenta lines) much higher than that observed (points).

2. The above determined MW mass range allows to calculate accurate orbits that are generally consistent with a first infall for most dSphs. For example 2/3 of them have eccentricities in excess of 0.66 (such as the LMC) and half of them with apocenter larger than 300 kpc (Fritz et al. 2018) when adopting the Bovy (2015) MW mass model that reproduces its kinematics.

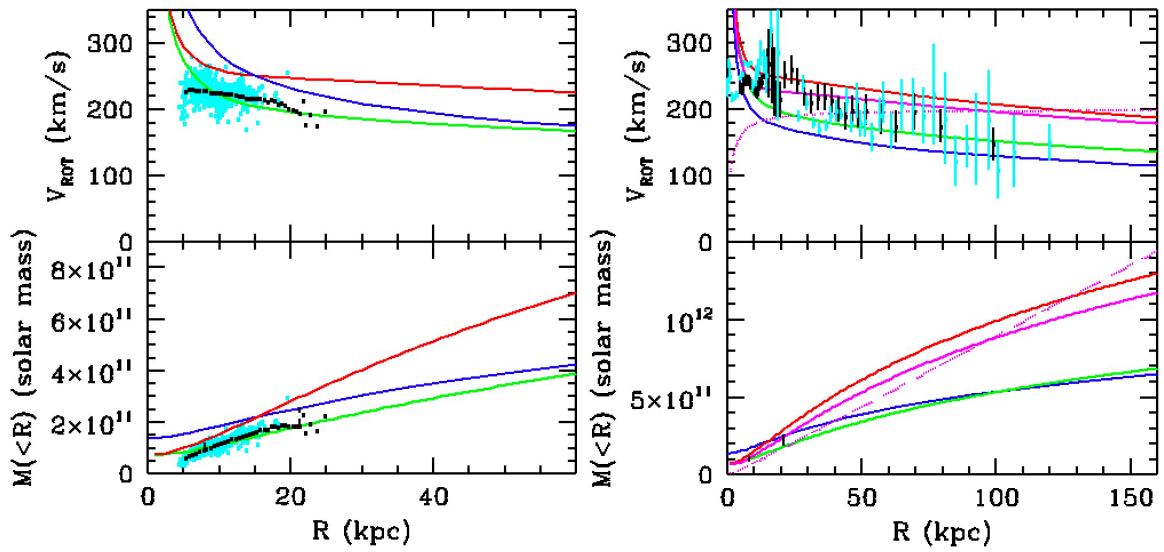


Fig. 1. Top left: Rotation curve of the MW. Black and cyan points represent the new determinations by Eilers et al. (2019) using massive stars, and by Mróz et al. (2019) using cepheids, respectively. The green line shows the Bovy (2015) model, the red line represents the Fritz et al. (2018) model for which they have multiplied the halo mass by 2, and the blue line shows the model of Sofue 2015. **Bottom left:** MW mass profile, same symbols as in the top left panel. **Top right:** Extended rotation curve of the MW. Black and cyan points with error-bars represent compilations from Huang et al. (2016) and Bhattacharjee et al. (2014), respectively. As in the left panels, the green, red and blue lines show the Bovy (2015) model, the Fritz et al. (2018) model for which they have multiplied the halo mass by 2, and the Sofue (2015) model, respectively. The magenta (full and dotted) lines show the models of McMillan 2017 and Irrgang et al. 2013, respectively. **Bottom right:** MW mass profile, same symbols as in the top right panel.

dSph progenitors are likely gas-stripped dwarfs due to the ram-pressure caused by the MW halo gas as it has been proposed by Mayer et al. (2001). Observations support this scenario because all dwarfs (but the Clouds) are gas-rich beyond 300 kpc and gas poor within 300 kpc (Grcevich & Putman 2009). The gas removal by ram-pressure induces a lack of gravity implying that stars are then leaving the system following a spherical geometry. Such a geometry ensures the dominance of tidal shocks over tidal stripping (Binney & Tremaine 2008) explaining the absence of tidal features in most dSphs (Hammer et al. 2019). MW tidal shocks increase the square of the velocity dispersion by $\sigma_{\text{MWshocks}}^2 = \sqrt{2} \alpha_{\text{MW}} g_{\text{MW}} r_{\text{half}}$ where g_{MW} is the MW gravitational acceleration and $\alpha_{\text{MW}} = 1 - \partial \log(M_{\text{MW}}) / \partial \log(D_{\text{MW}})$ (Hammer et al. 2018). This property reproduces quite precisely the observed dSph velocity dispersions as well as the fundamental relationships established from the observations (see Figs. 1-3 and 5-7 in Hammer et al. 2019).

The role of the gas during the process is essential. First, it would be very unlikely that dSphs progenitors were without gas since such objects are extremely rare in the field. Second, DM-devoid models made by Piatek & Pryor (1995) assumed gas-free progenitors, which implies a strong dominance of tidal stripping. There are

similar models (Kroupa et al. 1997; Klessen & Kroupa 1998; Iorio et al. 2019) that also assumed multiple orbits furthermore limiting the possibility that tidal shocks affect the dSph velocity dispersions.

3 Discussion and Conclusion

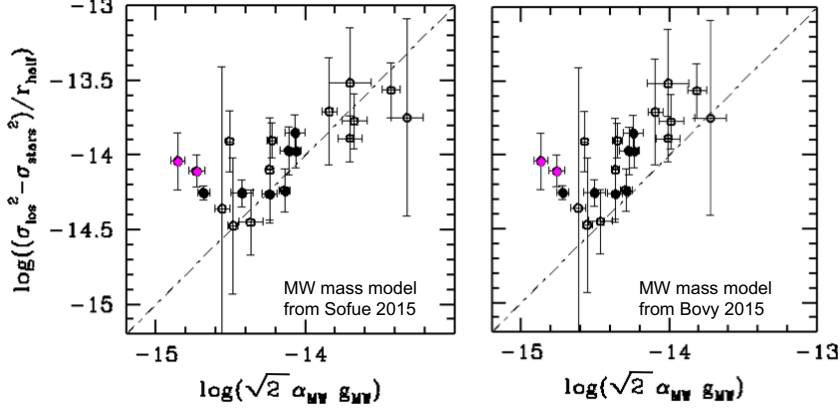


Fig. 2. Self-gravity acceleration $a_{DM} = (\sigma_{los}^2 - \sigma_{stars}^2) \times r_{half}^{-1}$ derived from DM estimates in dSphs compared (in logarithmic scale) to that due to MW tidal shocks, $a_{MWshocks} = \sqrt{2} \alpha_{MW} g_{MW}$. The left and the right panel show the relation for an adopted MW mass profile from Sofue (2015) and from Bovy (2015), respectively. Full (open) dots represent classic (non-classic) dSphs, respectively. Leo I and II are identified by points with magenta color since they do not fully obey the impulse approximation (see Hammer et al. 2019). Their location in the Figure can be well explained if they are affected by tidal stripping in addition to tidal shocks.

The DM content of dSphs derived by Walker et al. (2009) and by Wolf et al. (2010) comes from the measurement of the dSph-DM self-gravity acceleration projected along the line of sight, which is $a_{DM} = GM_{DM} \times r_{half}^{-2} = (\sigma_{los}^2 - \sigma_{stars}^2) \times r_{half}^{-1}$. Hammer et al. (2019) showed that over more than a decade, a_{DM} matches very well with the acceleration caused by MW tidal shocks on DM-free dSphs, which is $a_{MWshocks} = \sqrt{2} \alpha_{MW} g_{MW}$ (see Fig. 2). Why would the acceleration caused by the DM be precisely what it is expected from MW tidal shocks on DM-free dSphs? Why do MW tidal shocks predict that the DM mass-to-light ratio of Segue 1 is several thousand, while that of Fornax is around ten? The acceleration caused by the DM (a_{DM}) also strongly anti-correlates with the dSph distance from the MW (Hammer et al. 2019, see their Fig. 1). The probability that this is just a coincidence is only 3×10^{-4} , which can be conservatively considered as the chance that DM impacts the kinematics of dSphs.

We are aware that the above could seriously affect the paradigm of DM in MW dSphs, and then have an impact on the cosmological models, except if MW dSphs are not representative of the dwarf regime. It is not unexpected that these results would be met with some skepticism. Could this be contradicted by other properties, e.g., of their progenitors that are likely dwarf Irregulars (dIrrs)? The DM content of dIrrs that share a similar stellar mass range than dSphs is still not well constrained. The most massive dSph (e.g., Fornax and maybe Sculptor) progenitors can be found, e.g., in the smallest galaxies of the sample from Lelli et al. (2016), which includes the best studied rotation curves over a large mass range. The DM content of these small galaxies that are all dIrrs has been derived from their rotation curves and varies from none to large values, in particular within a radius similar to the half light radius that is adopted for sampling dSph dynamical properties (Walker et al. 2009; Wolf et al. 2010; Hammer et al. 2019). It appears very hard to assess rotation curves and velocity amplitudes in dwarf galaxies that are too irregular. Trying to identify possible progenitors of smaller dSphs (e.g., UFDs) that constitute the bulk of dSphs leads one to consider extremely small dIrrs, for which establishing their rotation curves can not be seriously attempted (McNichols et al. 2016; Oh et al. 2015; Ott et al. 2012). This is because these tiny objects are far from being represented by a thin disk geometry and also because their velocity amplitudes are similar to that of their dispersion, the latter being mostly associated to star formation and turbulence (Stilp et al. 2013).

Star formation histories of dSphs have been well studied especially for the most massive ones (Weisz et al. 2014). For Fornax (de Boer et al. 2013) it is consistent with a recent gas removal by ram-pressure and then

with the tidal shock scenario. While this also applies to Carina, Leo I and perhaps to Leo II, past histories of Sculptor, Sextans, UMi and Draco (Weisz et al. 2014) are perhaps more problematic. Why did the star formation in the Sculptor progenitor stop about 5 Gyr ago (de Boer et al. 2012) if it was still in isolation at a later time? Only a full hydrodynamical simulation with a well determined orbital history for Sculptor would help us to verify a potential inconsistency. Interestingly, recent simulations (Garrison-Kimmel et al. 2019) have shown that gas-rich dwarfs with Sculptor stellar mass and in isolation may have similar star formation histories than Sculptor, and this also applies to galaxies with smaller masses that form the bulk of the MW dSphs. The above may lead to a significant change of paradigm in our understanding of the MW dSphs, which could impact the determination of the lower end of the galaxy mass function. Next steps will be to verify if this is consistent with other dSphs of the MW, which total mass can be robustly determined without extrapolations.

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