DARK MATTER IN DWARF GALAXIES OF THE LOCAL GROUP*

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(Received October 18, 2011)

We review basic properties of the population of dwarf galaxies in the Local Group focusing on dwarf spheroidal galaxies found in the immediate vicinity of the Milky Way. The evidence for Dark Matter in these objects is critically assessed. We describe the methods of dynamical modelling of such objects, using a few examples of the best-studied dwarfs and discuss the sources of uncertainties in mass estimates. We conclude with perspectives for dwarf galaxies as targets for Dark Matter detection experiments.

DOI:10.5506/APhysPolB.42.2185
PACS numbers: 98.10.+z, 98.52.Wz, 98.56.–p, 98.62.Ck

1. Introduction

The population of dwarf galaxies in the Local Group offers a unique opportunity to test our theories of structure formation in the Universe. Starting from the Magellanic Clouds which were known since antiquity, the census of the dwarf galaxies in our immediate vicinity still grows. The sample of dwarf galaxies in the Local Group can be divided using the morphological criteria into classes of dwarf irregulars (dIrr) that are flattened, rotating, bright and still forming stars and dwarf spheroidals (dSph) which are rounder, faint and contain mostly old stellar populations dominated by random motions.

Dwarf galaxies of the Local Group tend to cluster around the two main hosts, the Milky Way and Andromeda, exhibiting a pronounced morphology–density relation: while dSphs are typically found close to one of the big galaxies, dIrrs occupy more isolated regions. The origin of this relation is an interesting issue that the theories of structure formation must address. Another question in which dwarf galaxies played a role is the so-called problem of missing satellites: the number of observed satellites of the Milky Way is

* Presented at the XXXV International Conference of Theoretical Physics "Matter to the Deepest", Ustroń, Poland, September 12–18, 2011.

much smaller than predicted by theories based on cold Dark Matter. Dwarf galaxies, especially nearby dSphs, have also drawn attention once a significant number of stellar velocities could be measured and their masses could be determined. These masses turned out to be much larger than could be explained by the stellar content indicating large amounts of Dark Matter present.

Observational properties of dwarf galaxies [1] are usually characterized by the total visual magnitude $M_{\rm V}$, the central surface brightness $\mu_{\rm V}$, the half-light radius (containing half the total luminosity) $r_{1/2}$, the ellipticity $e = 1 - b/a$ and the ratio of the rotation velocity to the velocity dispersion V/σ. The latter four quantities are plotted in figure 1 as a function of magnitude for the dwarf galaxies in the Local Group with –16 mag $< M_{\rm V} < -8$ mag using data compiled in [2]. The sample includes the eight "classical" best-

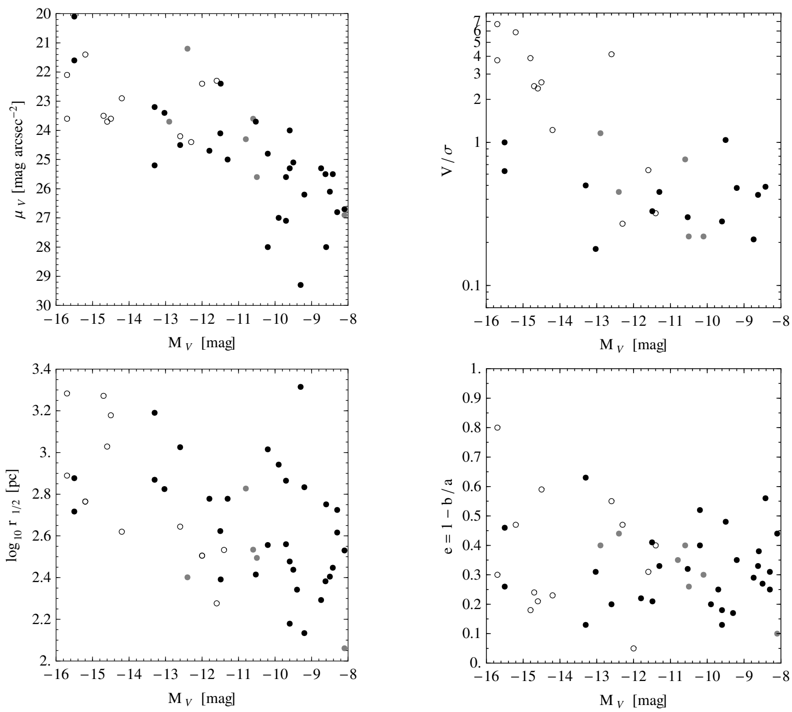

Fig. 1. Observational parameters of dwarf galaxies in the Local Group: the central surface brightness $\mu_{\rm V}$ (upper left panel), the half-light radius $r_{1/2}$ (lower left panel), the ratio of the rotation velocity to the velocity dispersion V/σ (upper right panel) and the ellipticity $e = 1 - b/a$ (lower right panel) as a function of the total visual magnitude $M_{\rm V}$. The open circles show the data for dIrr galaxies, filled black circles the data for the dSph and dSph/dE galaxies and grey circles for transitory dIrr/dSph dwarfs.

known dSph galaxies, satellites of the Milky Way: Carina, Draco, Fornax, Leo I, Leo II, Sculptor, Sextans and Ursa Minor with magnitudes in the range -13 mag $< M_{\rm V} < -8$ mag which all have low central surface brightness $\mu_{\rm V}$ (> 22.4 mag arcsec^{-2}) and small half-light radii (< 0.7 kpc). The properties of these eight dwarfs are listed in Table I. All classical dwarfs are believed to be characterized by large mass-to-light ratios between 10 and a few hundred solar units.

TABLE I

Properties of the classical dSph galaxies, satellites of the Milky Way.

Dwarf galaxy	$M_{\rm V}$ [mag]	$r_{1/2}$ [kpc]	$\mu_{\rm V}$ [mag arcsec^{-2}]	V/σ	$e = 1 - b/a$
Carina	-8.62	0.241	25.5	0.43	0.33
Draco	-8.74	0.196	25.3	0.21	0.29
Fornax	-13.03	0.668	23.4	0.18	0.31
Leo I	-11.49	0.246	22.4	0.33	0.21
Leo II	-9.60	0.151	24.0	0.28	0.13
Sculptor	-10.53	0.260	23.7	0.30	0.32
Sextans	-9.20	0.682	26.2	0.48	0.35
Ursa Minor	-8.42	0.280	25.5	0.49	0.56

In recent years we have witnessed discoveries of new dSph galaxies in the Local Group, mainly in the northern part of the Sloan Digital Sky Survey [3]. These new dwarfs are generally fainter and more irregular in shape than the classical ones but not more distant. If analogous discoveries follow in the southern hemisphere, they may significantly help to solve the problem of missing satellites. Spectroscopic studies of the stellar populations [4] of the faint dwarfs revealed quite large velocity dispersions and thus large masses for these dwarfs were estimated suggesting even higher Dark Matter content than in well-known dSphs. It has been speculated [5] that the characteristic masses of all dwarfs are of the order of 10^7 solar masses, independently of their luminosity. A more acceptable proposal [6] suggests instead a universal relation between the half-light radius and the mass contained within it.

2. Evidence for Dark Matter

Dynamical modelling of dSph galaxies relies on measuring the velocity distribution of stars in a galaxy and modelling it using methods based on the virial theorem or its extensions. The most common approach is to use the Jeans equation [7] which relates the velocity dispersion measured in the galaxy to the underlying gravitational potential. Currently available data comprise a few hundred up to more than two thousand stellar velocities measured in a single dSph galaxy which allows us to study the velocity dispersion profile as well as higher velocity moments [8]. Examples of such profiles are shown in figure 2 for the four classical dwarfs with most numerous data sets available at present [9].

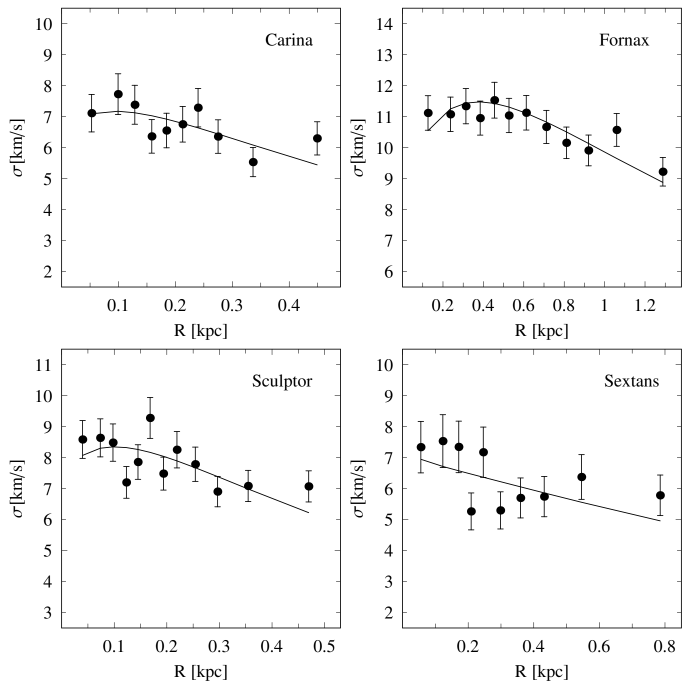

Fig. 2. Velocity dispersion profiles for the member stars in the four dSph galaxies: Carina, Fornax, Sculptor and Sextans. Errors indicate the sampling errors of the dispersion. Lines show the best-fitting profiles from fitting velocity dispersion profiles with the solutions of the Jeans equation.

Fitting the solutions of the Jeans equation to the measured velocity dispersion profiles allows us to constrain the properties of the mass content of the galaxy. If we assume that mass follows light, the problem can be reduced to fitting two parameters: the total mass M and the parameter of the velocity anisotropy of stellar orbits β. For the four dwarf galaxies from figure 2 such modelling yields constraints on these two parameters shown in figure 3 with stellar orbits remarkably close to isotropy ($\beta = 0$). The best-fitting masses translate to rather large mass-to-light ratios of the order of 10 solar units for Fornax and Sculptor and above 50 for Carina and Sextans [8], signifying the presence of large amounts of Dark Matter.

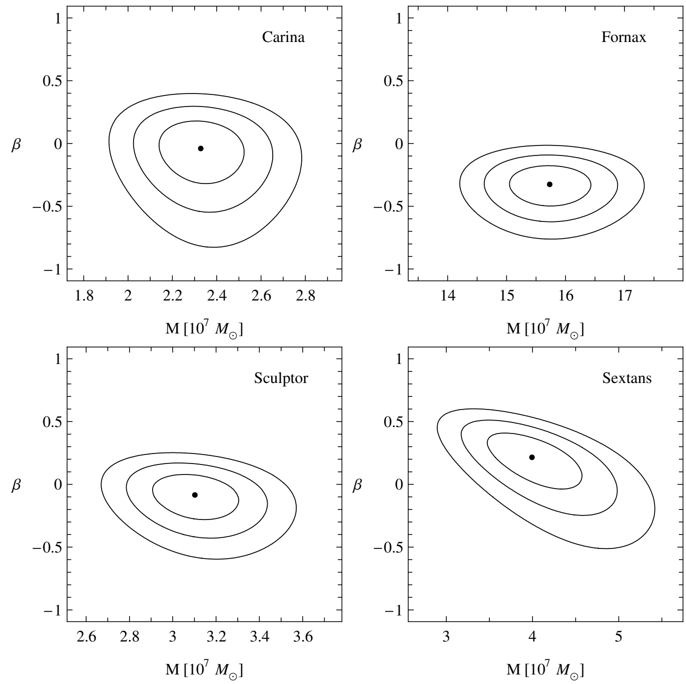

Fig. 3. The 1σ, 2σ and 3σ probability contours showing constraints on the two fitted parameters: the total mass M and velocity anisotropy β. The constraints follow from the sampling errors of the measured velocity dispersion profile. Dots indicate the best-fitting parameters.

The reliability of such inferences has been a subject of a long, on-going debate. One popular objection often raised is that Jeans modelling rests on the assumption that the galaxies are in equilibrium, while if they are strongly affected by tidal forces from the Milky Way, this may not be the case. Second, even if the objects are essentially self-gravitating and in equilibrium, the kinematic samples used for the modelling may be contaminated by tidally stripped stars counted as members. Third, binary stars present in the population may boost the measured velocity dispersion. In addition, the most popular assumptions in the modelling: that the objects are spherical and β is independent of radius (or zero everywhere) may be too simplistic.

Of all these objections, the contamination by tidally stripped stars seems to be the most serious issue. Using N-body simulations it has been demonstrated [10, 11, 12] that dwarf galaxies orbiting the Milky Way retain their identity and remain in relative equilibrium for billions of years in spite of being heavily stripped of stars and Dark Matter. The stripped material forms extended tidal arms, which, if pointing towards the observer, may significantly contaminate the samples increasing the measured velocity dispersion. Efficient procedures to deal with this contamination have been developed [10] and it has been demonstrated on artificial data generated from the simulations [13] that once the data are cleaned of such interlopers, the mass and anisotropy estimates based on Jeans formalism and its extensions are in good agreement with true values.

In particular, the velocity dispersion profiles shown in figure 2 were obtained from data preselected using such procedures. Note, that both the measured and the fitted velocity dispersion profiles in the figure are decreasing with the projected radius from the centre of the dwarf R, as expected for self-gravitating galaxies, and in contrast to contaminated samples where the dispersion tends to increase at large distances.

The best-fitting solutions of the Jeans equation shown in figure 2 were found with the assumption that mass follows light. This assumption is justified for dwarfs heavily affected by tides which tend to strip the (initially more extended) dark halo more effectively than the stars. However, certainly not all satellites of the Milky Way fall into this category, a notable example being the Draco dSph, where the models with mass following light fail to reproduce the data in a satisfactory way. If the parameters of the dark matter halo are allowed to vary, the modelling based on the Jeans equation alone is plagued by a strong degeneracy between the shape of the halo and the anisotropy parameter. In particular, the same dispersion profile can be reproduced by galaxy models with tangential orbits ($\beta < 0$) and compact dark haloes or radial orbits ($\beta > 0$) and extended haloes.

A way to overcome this difficulty is to extend the Jeans formalism to include higher (fourth order) velocity moment (the kurtosis) which is sensitive mainly to anisotropy. Once the anisotropy is constrained by kurtosis, the density profile of the dark halo can be constrained as well, so fitting both moments simultaneously allows us to estimate both properties. This procedure has been successfully applied to the Draco dwarf [14] giving a very high mass-to-light estimate of around 300 solar units for this dwarf.

Unfortunately, including higher velocity moments does not help to constrain the inner slope of the Dark Matter distribution in dSph galaxies. For example, it has been demonstrated for the Draco dwarf that the cuspy and a core-like Dark Matter halo fits the available data equally well [15]. Measurements of this property are important because they may help to solve the so-called cusp/core problem in dwarf galaxies, a tension between theoretical models which predict steep inner slopes and observations of rotationally supported dwarfs which tend to be reproduced better by cores in Dark Matter distribution.

3. Conclusions

The case for a high Dark Matter content in dSph galaxies of the Local Group is quite strong. The objects are found to contain significant amounts of Dark Matter even if the modelling is performed with very conservative assumptions such as the one that mass follows light and on samples which were subject to restrictive algorithms of interloper rejection. It has been demonstrated that the classical dwarfs, even if strongly affected by tidal force from the Milky Way can be reliably modelled by standard methods assuming virial equilibrium.

The high mass-to-light ratios of the classical dwarfs may turn out to be even higher in the case of the newly discovered population of ultra-faint satellites of the Milky Way. If the trend is confirmed, the fainter dwarfs may become excellent targets for experiments aiming for the direct detection of Dark Matter in the Universe via self-annihilation of Dark Matter particles. Dwarf galaxies are good candidates for such targets not only because of the high dark matter content but also because they have low astrophysical gamma ray backgrounds and they are small and localized so may easily fit in the field of view of many instruments.

Recently, observations of dwarf galaxies with the Fermi Large Area Telescope began to yield interesting constraints on the parameters of a variety of supersymmetric models that provide candidates for weakly interacting massive particles as Dark Matter [16]. Although no clear signal of annihilation has been detected from dwarf galaxies so far, upper limits on the annihilation cross-section can be obtained. The upper limits do not yet reach the interesting region of density parameter values compatible with the standard cosmological model, but are already able to exclude a significant number of supersymmetric models of particle physics.

This research and the author's participation in the XXXV International Conference of Theoretical Physics “Matter to the Deepest: Recent Developments in Physics of Fundamental Interactions” was partially supported by the Polish National Science Centre under grant N N203 580940.

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