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The internal kinematics and mass content of Local Group dwarfs from extensive spectroscopic surveys

G. Battaglia

Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy, e-mail: gbattaglia@oabo.inaf.it

Abstract. In this contribution I will discuss some of the recent, exciting progresses on the mass modeling of Local Group dwarf galaxies as made possible by the exploitation of large spectroscopic surveys of several hundreds individual stars per system.

Key words. Stars: kinematics and dynamics – Galaxies: dwarf – Local Group – dark matter

1. Introduction

Certainly one of the main challenges of modern astrophysics and particle physics is to find an answer (the correct answer!) to the question: what is the nature of dark matter?

Since the properties of dark matter (DM) particles are expected to influence the way structures in the Universe form and evolve, the comparison between predictions from cosmological models in a DM context and astrophysical observations of objects on a variety of scales have the potential of distinguishing between different DM models.

Such comparisons though have to deal with the difficulty that, being DM not directly observable, we can only make inferences on its properties by studying what we can actually observe, i.e. the baryons. This implies that simulations of structure formation need to be able to properly predict the resulting properties of baryonic structures by including the complicated and not-well understood physics of baryons, or that we need to compare predictions from DM-only simulations to our observations of the baryonic component of galaxies, clusters etc. When following the latter route, typically one tries to test predictions against observations of those baryonic structures most suited to perform specific tests and/or that have the largest discriminating power.

N-body DM-only simulations within the ΛCold DM framework give consistent and robust predictions regarding the functional form of the density profile of DM haloes, which should be cusped (e.g. Navarro et al. 1996; Merritt et al. 2006; Springel et al. 2008), and the mass function of DM sub-haloes around MW-sized hosts (see Springel et al. 2008, and references therein).

The early-type, low surface brightness dwarf galaxies found around the MW offer particularly interesting perspectives on both of these aspects: the well-known mismatch between the number of DM sub-haloes expected to surround MW-sized haloes and the number of satellite galaxies found around the Milky Way (MW) and M31 (Klypin et al. 1999; Moore et al. 1999) can illuminate the process of galaxy formation at small scales in the early Universe (e.g. Bullock et al. 2000; Benson et al. 2002; Somerville 2002) as well as providing insights into the properties of DM particles (Colín et al. 2000, 2008; Lovell et al. 2012). Furthermore, these galaxies display a unique feature, i.e. enormous dynamical mass-to-light ratios that reach up to 100s $M/L_{\odot}$, for classical dwarf spheroidals (dSphs) (e.g. Wilkinson et al. 2002; Walker et al. 2007b; Battaglia et al. 2008), and up to 1000s $M/L_{\odot}$ in the recently discovered class of Ultra Faint Dwarfs (e.g. for UFDs, Martin et al. 2007; Simon & Geha 2007). Such large dynamical M/L makes them the most DM dominated objects we know of, at every radius. Not only this allows us to neglect the dynamical contribution of baryons in the mass modeling of these systems, but makes them powerful probes of the central slope of the DM halo they inhabit as well as very good targets for example for detecting the annihilation signal of candidate DM particles.

It is then clearly important to determine the DM mass content and distribution of these faint galaxies. The Local Group contains several dozens of such systems that can be studied to this aim. Early-types dwarfs such as the dSphs and the UFDs are devoid of neutral gas; so that the only kinematic tracer available for mass modeling is the stellar component. This is actually the case also for several other dwarfs classified as irregulars or transition types because often their neutral interstellar medium has an irregular distribution and kinematics that prevents us to confidently use it for mass modeling. Stars in the early types dwarfs are dominated by random motions and with current facilities we can only determine one component of the velocity vector of individual stars in these galaxies, i.e. the velocity along the line-of-sight (l.o.s.). When determining the DM content and distribution of most Local Group dwarf galaxies, we are then extracting this information from the line-of-sight velocity distribution (LOSVD) of stars in these systems, in particular from the l.o.s. velocity dispersion $\sigma_{\rm l.o.s.}$, and in general treating them as spherical, non-rotating systems. In the following I concentrate on the MW classical dSphs, as these are the best studied early-type, low surface brightness dwarf galaxies.

2. Results from mass modeling

Already the first determination of the $\sigma_{\rm l.o.s.}$ of a MW dSph, attempted by Aaronson (1983) with only 3 (carbon) stars for Draco, hinted to a dynamical mass-to-light ratio about one order of magnitude larger than for globular clusters, where the latter are commonly regarded as dark-matter free objects.

This tentative result was later on confirmed by samples containing a few dozens member stars per galaxy (e.g. Armandroff & Da Costa 1986; Aaronson & Olszewski 1987; Hargreaves et al. 1994). These samples were still suitable for the determination of one single value for the l.o.s. velocity dispersion and not for exploring the radial behaviour of this quantity, which allows more information to be extracted on the DM mass density profile.

An increase in sample size became possible with multi-object spectrographs such as the KPNO/4 m Hydra multi- fiber positioner, and the AF2/Wide Field Fibre Optical Spectrograph on the WHT (Armandroff et al. 1995; Kleyna et al. 2001). But it was in the second half of the 2000s that a leap forward was made in the determination of the internal kinematic properties of dSphs, thanks to spectroscopic surveys of several hundreds individual stars per system (e.g. Tolstoy et al. 2004; Majewski et al. 2005; Muñoz et al. 2005; Battaglia et al. 2006; Koch et al. 2006; Westfall et al. 2006; Koch et al. 2007a; Walker et al. 2007a, 2009a; Battaglia et al. 2011). Nowadays accurate l.o.s. velocity dispersion profiles, $\sigma_{\rm l.o.s.}$, are available for all of the classical MW dSphs, in most of the cases probing as far out as to their nominal tidal radius (see Walker 2013; Breddels & Helmi 2013, for the most recent determinations). In the context of Newtonian dynamics, under the hypotheses of dynamical equilibrium and isotropic velocity distribution, in most cases the l.o.s. velocity dispersion profile given by King models that best fit the observed surface brightness profile of the stars clearly under-predict the observed $\sigma_{\rm l.o.s.}(R)$. If the assumptions hold, then this implies that the dynamical M/L is not constant, but increases with radius[1]; essentially, that the luminous component of dSphs is embedded in a more extended, massive DM halo.

Can more information on the density distribution of the DM be extracted from the analysis of the $\sigma_{\mathrm{l.o.s.}}$(R) of MW dSphs? Much of the mass modeling of these galaxies has relied on spherical Jeans analysis for stationary and non-rotating systems (e.g. Łokas 2001; Kleyna et al. 2001; Koch et al. 2007b; Gilmore et al. 2007; Walker et al. 2007b; Battaglia et al. 2008), due to dSphs relatively small *projected* ellipticities and dominant support from random motions. Unfortunately, when only one component of the velocity vector can be measured for the kinematic tracers (here the l.o.s. velocity of the individual stars), we cannot directly determine the value, and its possible radial variations, of the velocity anisotropy. This leads to the well-known "mass-anisotropy degeneracy": it is possible to find combinations of different DM distributions and anisotropies that can provide indistinguishable, very good fit to the observed $\sigma_{\mathrm{l.o.s.}}$(R) (see e.g. Fig.3c in Battaglia et al. 2008).

In principle, information on β could be retrieved from the shape of the LOSVD of the stars in the outer parts of the galaxy (e.g. Dejonghe 1987; Gerhard 1991, 1993; Wilkinson et al. 2002), in particular in the fourth moment of the distribution. Studies that have examined the behaviour of the 4th moment have reached different specific conclusions, finding a slightly tangential anisotropy for a given dSph, while others find a slightly radial anisotropy; however, the general consensus is that the LOSVD of stars in MW dSphs is very close to be Gaussian, also as a function of radius, meaning that the anisotropy is neither strongly radial nor strongly tangential (e.g. Łokas et al. 2005; Mateo et al. 2008; Łokas 2009; Amorisco & Evans 2012b; Breddels et al. 2013). The uncertainties in the determination of the 4th moment from current samples are not small enough to provide values of β of sufficient accuracy to break the mass-anisotropy degeneracy and gain more information on the DM density profile.

An alternative route that was put forward in the last years exploits a characteristic displayed by several MW dSphs: the presence of multiple "chemo-dynamical" stellar components, i.e. the fact that "metal-poor" and "metal-rich" stars are found to have different spatial distributions and kinematics. Battaglia et al. (2008) carried out a spherical Jeans analysis of the Sculptor dSph, modeling simultaneously its multiple stellar components and treating them as two independent kinematic tracers of the same potential. In this way, the mass-anisotropy degeneracy is partially relieved and stronger constraints could be placed on the density profile of the DM halo, preferring a cored DM profile instead than a cuspy NFW halo (although the latter is still statistically consistent with the data).

Walker & Peñarrubia (2011) combined the use of multiple stellar components with a recent result that shows that for a spherical system in dynamical equilibrium there exists a radius where the value of the integral mass M(r) is largely insensitive to β (Walker et al. 2009b; Wolf et al. 2010). Such radius is approximately equal to where the log-slope of the 3D stellar density profile is -3 (r_{-3}) and is very close to the 3D deprojected half-light radius. Given the different half-light radii of the "metal-rich" and "metal-poor" populations, this allows to estimate the mass of the system at two points, obtaining a slope. This analysis excludes at high significance that Sculptor and Fornax inhabit cuspy NFW halos and gives preference to cored DM profiles. It needs however to be noted that the method applies to l.o.s. velocity dispersion profiles that are constant with radius, while the "metal-rich" component, in particular in Sculptor, departs from this behaviour. In general the use of multiple stellar components appears to produce a preference for cored DM density profiles (see also Amorisco & Evans 2012a), although it needs to be fully investigated whether triaxiality may be driving the results (Kowalczyk et al. 2013).

[1] As discussed in Walker (2013), "if mass follows light, then the flat empirical velocity dispersion profiles of dSphs tend to imply unphysical values of the velocity anisotropy $\beta > 1$", where beta is defined as $\beta(r) = 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$.

Recently, mainly thanks to the growing samples of accurate l.o.s. velocities available for MW dSphs, sophisticated techniques like Schwarzschild modeling have started being applied to these systems (Jardel & Gebhardt 2012; Breddels et al. 2013; Breddels & Helmi 2013). Over the Jeans modeling, this technique has the advantage of providing distribution functions which are always positive and of yielding the velocity anisotropy of the system as an output. Even though applied to binned data (hence to l.o.s. velocity dispersion profiles and the 4th moment of the LOSVD(R)) rather than to the individual velocities and in the approximation of sphericity, very promising results have emerged from the work of Breddels & Helmi (2013): independently on the adopted model for the density profile of the DM halo, the best-fitting profiles yield very similar M(r) over a wide range of radii, approximately from r_{-3} to the last measured point. This means that we know with good accuracy what is the mass profile of MW dSphs over a large radial range, a remarkable improvement! Even though the analysis cannot distinguish yet whether the individual dSphs inhabit cored or mildly cuspy DM halos, the analysis provides an almost model independent measurement of the log-slope of the DM density profile close to r_{-3}, whose value can for example be compared to those of DM sub-haloes in cosmological simulations.

3. Next steps

The future directions in the mass modeling of MW dSphs will most likely want to exploit all the information contained in the wealth of data-sets already available, and that will be in the near future, for these galaxies. Attempts that are already under way concern the application of the Schwarzschild modeling technique to the discrete data-sets of individual velocities, avoiding the loss of information intrinsic to binning; the relaxation of the hypothesis of sphericity (at least for the luminous component, we do know that is not spherically distributed), and the inclusion of the constraints given by the different spatial distribution and kinematics of stars of different metallicity.

Future facilities like VISTA/4MOST, WHT/WEAVE will have the capability of providing larger samples of accurate line-of-sight velocities for classical MW dSphs. In order to optimize future observations, it would be desirable to be guided by the models: what type of information will we need to uniquely determine the density profile of the DM halo that dSphs inhabit? How larger the samples of individual l.o.s. velocities need be, at what location in the galaxy and with what accuracies should they be known? Will l.o.s. velocities ever suffice or are we really in need of obtaining the other components of the velocity vector?

Another crucial aspect to address concerns the interpretation of the results: do the DM halo properties that we measure today resemble the initial ones? How is the DM distribution modified by the influence of the MW potential and by baryonic effects?

Finally, there is no doubt that UFDs are extremely intriguing but very challenging objects on which to perform mass modeling. One reason among others is the paucity of targets bright enough to obtain accurate velocities with current facilities, which makes the samples of l.o.s. velocities in UFDs similar to the early samples for dSphs. Will significant progress on determination of the DM distribution in UFDs have to wait for multi-object spectrographs on Extremely Large Telescopes?

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