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# Chemical properties of Local Group dwarf galaxies

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**Abstract.** Our Local Group contains a sizeable population of dwarf galaxies. In this review article I will discuss the opportunities that the study of the chemical properties of individual stars in these systems gives us of addressing fundamental questions concerning galaxy formation and evolution from the smallest scales to those of large spirals.

**Key words.** Stars: abundances – Galaxies: evolution – Galaxies: formation Galaxies: dwarf – Local Group

## 1. Introduction

The current - and ever increasing - census of the Local Group (LG) counts about 70 dwarf galaxies, which clearly outnumber the larger systems, i.e. the two Magellanic Clouds, Milky Way (MW), Andromeda, M32 and M33. This sizeable population of dwarf galaxies so conveniently located close to us makes of the LG a goldmine for resolved stellar population studies of these systems.

Accurate star formation histories (SFHs) dating back to the earliest times can be extracted from colour-magnitude diagrams (CMDs) reaching below the oldest main-sequence turn-off (MSTO); spectroscopic observations can deliver chemical properties and line-of-sight velocities of large samples of individual stars, allowing us to explore the chemical evolution, internal kinematic properties and disentangle the presence of multiple stellar components and sub-structures. Beside this wealth of information, a great advantage of resolved stellar population studies is the possibility of extracting from the data information on the *time evolution* of a system by targetting individual stars with ages spanning its full life-cycle, from the latest episodes of star formation back to the earliest times (low-mass stars have lifetimes that exceed an Hubble time). *Resolved stellar population studies hence allows us to address fundamental questions of galaxy formation and evolution, from a perspective that could not otherwise be investigated.*

In this article I will mainly focus on resolved stellar population studies of Local Group dwarf galaxies, with the aim of highligthing some questions that I find particularly compelling and for which the study of the chemical properties of individual stars in these systems can be enlightening.

• *What drives the evolution of the most numerous galaxy population?* As the most numerous galaxy population, dwarf galaxies are of great astrophysical importance as they represent the most common mode of galaxy formation. One way of investigating what processes drive the evolution of the population of dwarf galaxies, whether environmental or internal mechanisms, is to try and understand the origin of the variety of dwarf galaxy-types that we observe today: the late-types, i.e. those containing H I and that are presently forming stars (the dwarf irregulars, dIrrs) or being quiescent (the transition types, dT), and the early-types, devoid of H I, passively evolving and in general dominated by ancient stellar populations, >10 Gyr old (mainly dwarf spheroidal galaxies, dSphs).

Clear evidence that the fate of all galaxies, both dwarfs and large ones, is not independent of environment is given by the "morphology-density relations" exhibited by galaxy groupings at various scales (galaxy groups, clusters..), that sees early-types living preferentially in higher density regions with respect to the late-types. In the LG the "morphology-density relation" manifests itself in the early-type dwarfs being found within 300kpc from the large spirals while the late-types have larger distances (e.g. van den Bergh 1999). It is then plausible that the interaction with the large LG spirals may have transformed the late-types into early-types. On the other hand, the existence of dSphs and dTs (Cetus, Tucana, Aquarius, VV124) at large distances from both the MW and M31 may be telling us that also internal mechanisms could be shaping dwarf galaxies; for example the capability of sustaining star formation until the present-day could be related to the potential well of these small galaxies and/or to the amount of angular momentum (see below). In Sect. 3 I will discuss what hints the analysis of the chemical and internal kinematics of stars in LG dwarfs provide us on the mechanisms that drive the evolution of these systems.

• *The build-up of large galaxies* How strongly LG dwarf galaxies interact with their environs has consequences also for the assembly of large systems. Dwarf galaxies appear to be responsible, at least partially, for the build-up of larger galaxies, as suggested by the presence of streams/substructures around our own MW (e.g. Ibata et al. 1994; Belokurov et al. 2006), M31 (e.g. McConnachie et al. 2009) and galaxies outside of the LG (e.g. Martínez-Delgado et al. 2009; Moore et al. 1999; Rich et al. 2012).

According to the ΛCold Dark Matter (ΛCDM) framework of structure formation, stellar haloes in particular are the galactic structures predominantly formed by the debris of disrupted satellite galaxies (e.g. Bullock & Johnston 2005; Cooper et al. 2010). Some of the accreted small galaxies may survive until present and form the satellite system of the host. In this context, the early-type dwarf galaxies found in the surroundings of the MW and M31 are the natural candidates to have been the survivors of this accretion process. The comparison of the chemical patterns of stars in stellar haloes to those in the satellite galaxies is recognized as a very direct way to identify what type of small galactic systems contributed to forming larger galaxies. Such information is best extracted from high resolution spectroscopy and, with current facilities, the MW satellites are the external galaxies for which such analyses can be readily carried out (see Sect. 4).

• *The low end of the galaxy luminosity/mass function* Recent discoveries of LG stellar systems with extremely low surface brightness and luminosity (down to $\mu_V \sim 31$ mag arcsec$^{-2}$ and $M_V \sim -1.5$, respectively) are making us delve into debates over what was previously thought to be a simple matter: classifying an object as a galaxy rather than a stellar cluster. Prior to these discoveries (see Belokurov 2013, for a review), which we mainly owe to the SDSS, the faintest known galaxies were the "classical" MW dSphs (perhaps better named as "pre-SDSS" dSphs), which their large size would make easily distinguishable from globular clusters (e.g. Kormendy 1985). Nowadays not only has this separation in size disappeared, but some of the "post-SDSS" systems are less luminous than the great majority of globular clusters, and as extended as the largest ones of those. The most extreme, such as Segue and Segue 2, are less luminous than a single star at the tip of the red giant branch (RGB) (Martin et al. 2008; Belokurov et al. 2009)! Calling these stellar systems "galaxies" would be an act of courage (or a leap of faith, depending on the point of view), were it not backed up by a set of properties that support this classification (see e.g. Willman & Strader 2012). Understanding whether these are galaxies, stellar clusters or others, is not just a matter of nomenclature, but it carries important implications as we are basically defining the smallest baryonic structures that could be linked to dark matter subhaloes; and if galaxies can be as luminous and extended as stellar clusters, we ought to explain why in some cases nature chose to form a "galaxy" rather than a "stellar cluster" with the same amount of baryons distributed over similar spatial extents.

Since in principle these new discoveries may represent the lowest luminosity/surface brightness end of the dSph population, hereafter I will refer to them as the faintest MW dSphs or "post-SDSS" dSphs. In Sect. 5 I will discuss the uncertainties related to their classification as galaxies and the promising avenue that chemical abundances provide.

## 2. Spectroscopy of individual red giant branch stars

While the interstellar medium and young stars give us the end point of the chemical evolution of galaxies, here we are mostly interested in the added value given by observations of stars spanning a large age range. RGB stars are handy targets: stellar evolutionary models tell us they span age ranges from ∼1.5Gyr to the oldest times; they are also very bright, hence accessible for spectroscopic observations out to large distances (see for example the works from Leaman et al. 2009 and Kirby et al. 2012 on RGB stars in WLM and VV124, at ∼1Mpc and 1.4Mpc, respectively).

Several methodologies, each one with advantages and disadvantages, have been explored in the literature in order to extract elemental abundances from spectroscopic data of RGB stars obtained at various resolving power.

For example, in MW dSphs the metallicity ([Fe/H]) of RGB stars has been measured directly from dozens of Fe- lines in high resolution spectra, R$\gtrsim$20000 (e.g. Koch et al. 2008; Letarte et al. 2010; Lemasle et al. 2012, see references in Tolstoy, Hill & Tosi 2009); from a smaller set of Fe- lines in spectra at intermediate resolution, R ∼6500, with spectral synthesis (Kirby et al. 2010); via widely tested calibrations of the equivalent width of near infrared Ca II triplet lines (e.g. Tolstoy et al. 2004; Battaglia et al. 2006; Koch et al. 2006; Martin et al. 2007; Simon & Geha 2007; Koch et al. 2007; Battaglia et al. 2011) typically at R∼6000 (but down to R∼2500 for further away LG dwarfs, see e.g. Fraternali et al. 2009; Leaman et al. 2009).

Adopting a method rather than another one implies a trade-off between sample size, telescope time, accuracy achieved. Clearly the requirements depend on the type of analysis to be carried out; for example, for an understanding of the general wide-area metallicity properties of a galaxy the accuracy needed on the individual [Fe/H] measurements need not be as small as if one wants to pin-down the shape of the tails of the metallicity distribution function. Also, high resolution spectroscopic observations of individual RGB stars are currently out of reach in distant LG dwarf galaxies: for MW dSphs like Carina and Fornax FLAMES/GIRAFFE R∼20000 spectroscopic observations have been carried out for targets down to $I \lesssim 17.5$-18 (Letarte et al. 2010; Lemasle et al. 2012); at the distance of Carina, ∼100kpc, this corresponds to 1.5-2 mag below the tip of the RGB; probing down to 2mag below the tip of the RGB for galaxies at 400kpc/1Mpc would mean going as faint as $I$ ∼21/23.

As a guideline, it can be said that at present [Fe/H] measurements accurate to ±0.2-0.3 dex are within reach for individual RGB stars in galaxies out to the LG outskirts from intermediate resolution spectroscopy, while the abundance of $\alpha$- elements is restricted mostly to MW satellites.

## 3. Insights into the evolution of dwarf galaxies

Even if found at close distances, the least luminous MW satellites contain only an handful of RGB stars, which significantly limits the num-

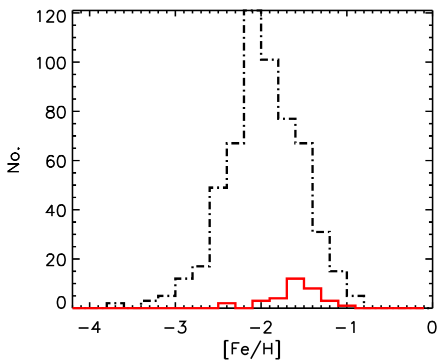


**Fig. 1.** The metallicity distribution function of probable member stars in the Sculptor dSph as derived in Battaglia & Starkenburg (2012) and from the much smaller sample of the early study of Tolstoy et al. (2001).

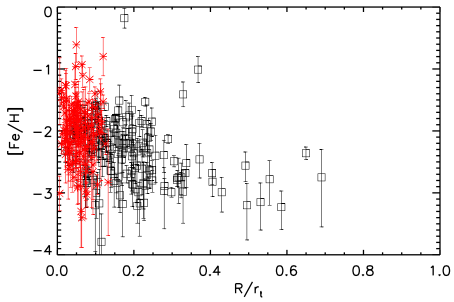


**Fig. 2.** [Fe/H] of probable member stars in the Sextans dSph as a function of the ratio between the projected elliptical radius and the nominal tidal radius. A spatial variation in the metallicity properties of this galaxy is visible in the sample of Battaglia et al. (2011) that covers out to large distances from the center (squares with error-bars, 174 members) but not in the sample of Kirby et al. (2010) as this covers only the central regions (asterisks with error-bars, 141 members). Note that the two samples contain a similar number of stars.

ber of targets within the reach of intermediate resolution spectroscopic observations even on 10m telescopes (see for example the works from Martin et al. 2007; Simon & Geha 2007).

On the other hand, the intrinsic luminosity, surface brightness, distance and extent on the sky of the "classical" MW dSphs makes them an excellent match to the capabilities of wide-area multi-object spectrographs mounted on 8m-class telescopes. Metallicities for several hundreds RGB stars per system have already been obtained for all of the MW "classical" dSphs (e.g. Tolstoy et al. 2004; Battaglia et al. 2006; Koch et al. 2006, 2007; Kirby et al. 2008; Gullieuszik et al. 2009; Kirby et al. 2010; Starkenburg et al. 2010; Battaglia et al. 2011), in most cases out to their nominal tidal radius.

The range of [Fe/H] values displayed by the stars can span 2-3dex, up to almost 4dex for the brightest MW dSph, i.e. Fornax. This is a much larger range of values than what revealed from earlier studies, as a consequence of the smaller sample sizes, as shown in Fig. 1. Such a large range of [Fe/H] values should be indicative of the capability of these small systems to hold on to their interstellar medium, hence of their potential well; it would be interesting to see whether reproducing the metallicity distribution function (MDF) could aid mass determinations of these galaxies, since the analysis of the internal kinematics of the objects can only directly constrain the mass enclosed within the region probed by the data, while in principle the dark matter halo of these galaxies is expected to be much more extended than the stars (e.g. Peñarrubia et al. 2008).

The low end of the MDF is the focus of several studies as the lowest metallicity stars carry information on the earliest stages of chemical evolution in these galaxies, informing us on the properties of the interstellar medium out of which these galaxies formed in the early Universe and potentially also on the characteristics of Pop III stars. To date, stars as metal-poor as [Fe/H]= -3.96 have been found in MW dSphs (Tafelmeyer et al. 2010, see also Frebel et al. 2010), but it is not excluded that even lower metallicity stars may be discovered, which in principle leaves open the possibility that these galaxies formed out of a pristine medium.

An interesting feature of several MW dSphs is that their metallicity properties vary spatially, with the inner regions being in average more metal-rich than the outer parts (Tolstoy et al. 2004; Battaglia et al. 2006; Koch et al. 2006; Battaglia et al. 2011). Such variations are found to occur on scales larger than 1-2 core radii, so that they can be detected only if the data reach out to large enough distances. An example is shown in Fig. 2, where I plot the [Fe/H] measurements of stars in Sextans as a function of their projected radius for two samples coming from independent works, containing a similar number of stars but with very different spatial extent.

The spatial variations of metallicity properties in MW dSphs are essentially telling us that the inner parts underwent a more extended chemical enrichment than the outer parts. The responsible mechanism has not been identified yet, although some possibilities can be put forward. Ram-pressure stripping can be more effective at removing the gas from the outer parts, in which case one would not expect to see such metallicity variations in those dwarf galaxies found far from the large spirals. In principle gas and metals could be most efficiently expelled from the outer parts in objects with a lower potential well, in which case a correlation with the total mass should be observed, although this does not appear to be backed-up by the latest measurements of the dark matter content in these galaxies (see Fig. 6 in Breddels & Helmi 2013, within the region where the mass content can be accurately derived). Angular momentum could also play an important role by means of a "centrifugal barrier" mechanism, which slows down the infall of gas into the dwarf center in higher angular momentum dwarf, allowing star formation and chemical enrichment to proceed everywhere (Schroyen et al. 2011). Interestingly, Leaman et al. (2013), analyzing a sample of 6 MW classical dSphs, together to 3 M31 dEs, the WLM dIrr and Magellanic Clouds, note a trend for steeper negative metallicity gradients for those dwarfs with a lower support from rotation (as from the $v/\sigma$ of the stellar component). As the authors point out, there are several caveats with the analysis, among which the possible effect of tidal disruption on the M31 dEs (e.g. see Choi et al. 2002, for tidal disruption signs in NGC 205), as well as the difficulties in associating a $v/\sigma$ to the complex stellar populations of the MCs, and the fact that the only actual *dwarf* irregular is WLM. At present, with a $v/\sigma \sim 1$ and no detection of a metallicity gradient, Tucana would appear to follow this general trend, although these results are derived from a small sample of only 17 member stars (Fraternali et al. 2009). The isolated VV124 dT appears to show a slight negative metallicity gradient for an upper limit of the $v/\sigma < 0.91$ (Kirby et al. 2012). The investigation of more dIrrs, transition types and the only two dSphs found far from the large spirals (Cetus and Tucana) spanning a range in $v/\sigma$ and mass shall provide clues as to the influence of environmental versus internal processes in setting the spatial metallicity properties in the dwarf galaxy population.

So far, however, information on the wide-area metallicity and internal kinematic properties of the evolved stellar component of most LG dIrrs, dTs and the isolated Cetus and Tucana dSphs is either lacking or restricted to small samples because the distance of these galaxies imply large investments of telescope time; the only exception being the works of Leaman et al. (2009, 2012) on WLM based on 180 stars, comparable to what is available in the literature for some of the less well studied MW "classical" dSphs.

Recently, Kirby et al. (2013) derived metallicities of individual RGB stars for other 6 among LG dIrrs and dTs and compare them to their sample of MW dSphs. The authors ask the interesting question of whether by fitting the metallicity distribution functions (MDF) with simple, analytical, chemical evolution models may reveal a difference in the gas inflow/outflow history as function of dwarf type. At present, there does not appear to be a clear preference with dwarf type, but, as the authors point out, the simple models used, which e.g. assume the instantaneous recycling and mixing approximations, are not the best suited to account for the complex star formation and chemical evolutionary history of dwarf galaxies, as well as for the possible impact of environment. ¿From an observational perspective, in my view, an important step is also to account for the fact that possible spatial variations in the metallicity properties of the galaxy make the shape of the MDF sensitive to the spatial coverage of the data-set (see Fig. 1) and, consequently, may drive the best-fitting chemical evolutionary model.

In early works, where the metallicity of RGB stars in the further away LG dwarfs was estimated photometrically, it was inferred that dSphs typically had experienced a much more efficient chemical enrichment than dIrrs of similar luminosity, as suggested by the two different luminosity-metallicity relations for these two class of galaxies (e.g. Grebel et al. 2003). This would pose problems in creating dSphs out of dIrrs that simply lose their gas. However, as it was pointed out by the authors, photometric metallicity determinations of RGB stars are prone to the age-metallicity degeneracy, which can only be broken with spectroscopic measurements. The work of Kirby et al. (2013) represents the first determination of a stellar mass-[Fe/H] relation for late-type dwarf galaxies as determined from the same stellar tracers (RGB stars) and homogeneous methodology (spectroscopically and applying the same analysis technique). Even though there is no spectroscopic determination yet of the mean [Fe/H] of Sex A,B, NGC 3109, SagDIG, i.e. those dIrrs that were in the worst agreement with the luminosity-[Fe/H] relation of dSphs in the work of Grebel et al. (2003), the re-determinations for Aquarius, Pegasus and Leo A are about 0.5dex more metal-rich than the photometric determinations, bringing them in agreement with the luminosity-[Fe/H] relation of dSphs. In the Kirby et al. (2013) work the two dwarf types follow nearly identical relations, which removes the specific problem of the luminosity-[Fe/H] relation in making dSphs out of dIrrs. A similarity in the chemical enrichment of the various dwarf types is also given by the works of the LCID team (Gallart & Lcid Team 2007; Hidalgo et al. 2009; Monelli et al. 2010b,a; Hidalgo et al. 2011), in which the age-metallicity relations derived from very deep CMDs of a sample of isolated LG dwarfs (2dIrrs, 2dTs and 2dSphs) agree very well with each other (C.Gallart, presentation at the EWASS 2013, Turku, Finland, see Fig. 3); the 2 dSphs shows a slightly faster chemical enrichment after the first couple Gyrs

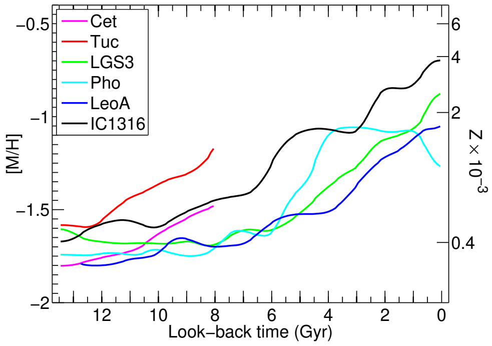


**Fig. 3.** Age-metallicity relation for the LCID sample of 6 isolated LG dwarf galaxies (2 dSphs, 2 dTs and 2 dIrrs); see references in the main text.

of evolution, perhaps a sign that they had already started the process of losing their gas.

There is much information encoded in the chemical properties of the evolved stellar components of galaxies. The investigation of the wide-area metallicity properties, the internal kinematics and (total) mass content of the evolved stellar component of the distant dIrrs, dTs and dSphs should allow for a deep understanding of what determined the origin of the various dwarf types, allowing at the same time to neglect the impact of the interaction with the large LG spirals, which is a large unknown in the evolution of the MW and M31 dSphs.

## 4. The assembly of the Milky Way halo

The chemical properties of MW dSphs have been analyzed in the past years also at the light of the information they could provide on the progenitor systems of the MW stellar halo. Here the questions that one wishes to answer are: is the MW stellar halo compatible with having been formed out of shredded MW dSphs? If not, what can we learn about the conditions out of which the halo formed? Stellar haloes of most simulated MW-like systems are expected to have acquired the majority of their stars >8 Gyr ago (e.g. Cooper et al. 2010); given that, depending on the formation time of the MW stellar halo, the dSphs that we observe today may have had some extra Gyr of evolution with respect to its progenitors, one typically concentrates on comparing the properties of the oldest/most metal-poor stars.

The low metallicity tail (at [Fe/H] <-2.5) of the MDF of dSphs, as based on direct determinations of [Fe/H] (Kirby et al. 2008) and on determinations from the CaT EW- [Fe/H] relation calibrated down to [Fe/H]=-4 (Starkenburg et al. 2010), is consistent with what observed for the MW stellar halo (e.g. Schörck et al. 2009) and may be telling us that dSphs experienced a similar early evolution in their chemical enrichment as the progenitors of the MW stellar halo.

The ratio of $\alpha$- elements over Fe is a well-known useful tool in this context as it acts as "clock" of the initial star formation history of a galactic component. Interestingly, over the years it was shown that the [$\alpha$/Fe] vs [Fe/H] properties of halo stars in the Solar Neighbourhood differ significantly from those of stars in the MW satellite galaxies (e.g. Shetrone et al. 2003; Tolstoy et al. 2004; Venn et al. 2004; Cohen & Huang 2009; Tolstoy et al. 2009; Letarte et al. 2010). Halo stars have nearly constant, super-solar [$\alpha$/Fe] over their full range of [Fe/H] values, interpreted as indication that the halo stars formed in regions with such a high star formation rate that only SNe II contributed to their chemical enrichment (e.g. Gilmore & Wyse 1998). On the other hand, stars in "classical" MW dSphs (we concentrate on this as they probe a much larger [Fe/H] regime than "post-SDSS" dSphs) start at nearly constant, super-solar [$\alpha$/Fe] and then decline to solar or even under-solar values. The position of the decline ("knee") indicates the metal-enrichment achieved by the galaxy once SNe Ia start to be important for the chemical evolution (e.g. Tinsley 1979; Matteucci & Brocato 1990) and is seen to vary in various systems: in Draco, it is located at [Fe/H] $\sim$ -2.5 (e.g. Cohen & Huang 2009), in Sculptor at [Fe/H] $\sim$ -1.6 (see Tolstoy et al. 2009); in most of the dwarfs there is not enough information to pin-down the [Fe/H] of the decline, but e.g. in Fornax it must have occurred at [Fe/H]$\lesssim$-1.5 (Letarte et al. 2010).

If we are to reconcile the chemical abundances of MW halo stars with a scenario in which the halo is formed out of disrupted smaller galaxies, one can envisage at least the following two possibilities:

1. *If the chemical abundances of halo stars in the Solar Neighbourhood are representative of the whole of the MW halo,* we then need building-blocks where the chemical evolution was such to result into flattish, super-solar [$\alpha$/Fe] vs [Fe/H] trend, hence shredded before SN Ia started to importantly contribute to their chemical evolution. Carina does not appear to be a good candidate as it shows a much larger scatter in [$\alpha$/Fe] with respect to MW halo stars of similar metallicity (e.g. see Lemasle et al. 2012); objects like Draco have a "knee" at very low metallicity (see above), hence could contribute only to a small fraction of the halo. On the other hand, Sculptor stars have similarly constant and super-solar [$\alpha$/Fe] as stars in the MW stellar halo out to [Fe/H] $\lesssim$-1.6, after which their [$\alpha$/Fe] start declining. Observationally, the "knee" in the Sculptor dSph is dated around 2±1Gyr from the start of star formation (de Boer et al. 2012), in agreement with theoretical expectations. Hence, if Sculptor is a good example of the survivor of one of these building-blocks, the halo must have been assembled very fast, within 2±1Gyr from the start of star formation in the building-blocks. But then, what type of object formed the part of the halo at [Fe/H] >-1.6, since to-date no MW dSph exhibits similar [$\alpha$/Fe] ratio as the halo at those metallicities? There are very little data available in the literature, but Sagittarius may display [$\alpha$/Fe] ratio compatible with those of the halo out to [Fe/H]~-1 (Chou et al. 2010).
2. *The chemical abundances of halo stars in the Solar Neighbourhood may* **not** *be representative of the whole of the MW halo*. In fact, a possible dual nature for the MW halo, with an inner and outer halo with different characteristics and formation mechanisms, was suggested by Searle & Zinn (1978) on the basis of the properties of the MW globular cluster system. More re-

cently, the metallicity and kinematic properties of a sample of ~10000 halo stars from SDSS strongly supported this hypothesis (Carollo et al. 2007; de Jong et al. 2010; Sesar et al. 2011; Schlaufman et al. 2012, to mention only a few other studies that go in this direction). The kinematic properties of outer halo stars appear compatible with a formation via the dissipationless accretion of stars formed in small dwarf-like systems, while instead the inner halo could have been formed by the dissipative merging of gas-rich protogalactic fragments (e.g. Gilmore et al. 1989). Different formation mechanisms for the inner and outer halo are also suggested by samples of solar neighbourhood stars for which is possible to infer orbital parameters/3D kinematics: e.g. in the seminal work of Nissen & Schuster (1997), the elemental abundances of halo stars with larger apocenter or with a retrograde kinematics have typically lower [$\alpha$/Fe] ratios than the rest (see also Nissen & Schuster 2010, and references there-in).

Carollo et al. (2007) showed that at [Fe/H]$\gtrsim$-2 the solar neighbourhood samples of halo stars are dominated by the inner halo, and we note that this is the metallicity regime where we see the largest discrepancies between the elemental abundances of halo and dSphs stars. Determinations of the chemical properties of *in-situ* outer halo stars in this metallicity regime will offer revealing information onto the build-up of the MW stellar halo (Battaglia, Shetrone, Jablonka in prep.)

## 5. To be or not to be a galaxy?

Since to-date no statistically significant amounts of dark matter have been measured in stellar clusters, while dwarf galaxies appear to be very dark matter dominated, the classification as galaxies of the new faint stellar systems discovered in SDSS around the MW has mainly relied on their internal kinematics. If their line-of-sight stellar velocity dispersion ($\sigma_{\rm l.o.s.}$) would suggest dynamical mass-to-light ratio larger than what could be due to their stellar component assuming reasonable initial mass functions, then the system would be classified as a galaxy. Translating a value of stellar velocity dispersion into a dark matter content for systems with such low measured velocity dispersions (of the order of 5 km/s) encounters several complications: a) since for these objects the measured $\sigma_{\rm l.o.s.}$ is often of the order or even smaller than the velocity errors on the individual measurements, very accurate determinations of the velocity errors are needed; b) the orbital motion along the line-of-sight of unidentified binary stars can inflate the measured $\sigma_{\rm l.o.s.}$, in principle causing a dark-matter free object to mimic large dynamical M/L (McConnachie & Côté 2010); c) these stellar systems may have suffered from tidal disturbance from the MW potential that may place them out of dynamical equilibrium, in which case the kinematics of their stars would be not properly tracing the underlying dark matter potential.

The chemical properties of the stars in these objects could be more straightforward to interpret as they are not affected by these complications. Commonly, stellar clusters do not appear to show spreads in [Fe/H] (other than peculiar systems like Omega Centauri, in general regarded as the remnants of a disrupted larger dwarf galaxy, see contribution by A. Mucciarelli, this issue), and this is interpreted as their potential well not having the sufficient depth to retain ejecta from supernovae explosions. Since the globular cluster mass needed to retain SN ejecta are >few $\times 10^6 M_\odot$ (e.g. Dopita & Smith 1986; Baumgardt et al. 2008), a significant spread in [Fe/H][1] in systems with lower stellar masses would suggest the presence of a surrounding dark matter halo.

As long as we can safely state that stars in globular clusters below a certain mass threshold do not exhibit spreads in [Fe/H], this appears a very promising way for classifying these new extreme stellar systems and future ones that may be discovered. For example, in the case of Segue 2, whose revised value of the

[1] Here it is assumed that the measurement errors are factored in the determination of the intrinsic [Fe/H] spread.

velocity dispersion (Kirby et al. 2013) would make it consistent with being dark matter free, the chemical approach is the only one that keeps its classification as a galaxy “alive”.

For such very faint, low surface brightness stellar systems is not as easy task to gather samples of stars which can be considered as highly likely members. The problem is worsened for those of these systems whose location on the sky and systemic velocities are such that it becomes very challenging to readily identify what stars belong to the dSph and which ones are MW contaminants. The complicated structure of the MW halo muds even more the picture, as several of the low luminosity, new discoveries appear to be associated with MW halo streams (see Belokurov et al. 2009; Belokurov 2013, and references therein). Concentrating on Segue 2, which at present is considered as the lowest luminosity known galaxy (900 Lsun!), its spread in [Fe/H] is determined out of 10 stars, several of which on a radial velocity vs [Fe/H] plane lie on what seem to be a region highly contaminated by MW stars. The identification of clean samples of target stars has already proven to be tough for systems like for example Willman 1 and Hercules, resulting in important changes in their measured properties, even when using a number of membership indicators (e.g. Martin et al. 2007; Simon & Geha 2007; Siegel et al. 2008; Adén et al. 2009a).

Excluding that contamination may affect the determined intrinsic kinematic and chemical properties of these faintest of systems appears to me as an essential step for a robust understanding of what is the faint limit of the galaxy luminosity function.

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