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Using radial metallicity gradients in dwarf galaxies to study environmental processing

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Abstract. The observed morphology-density relation in the Local Group suggests that some amount of environmental processing has occurred, however the nature and efficiency of tidal and ram pressure stripping is not well constrained. A possible avenue to test these processes is to study the radial distribution of metallicity and angular momentum in dwarf galaxies of different environments. Using spectroscopic abundances in the isolated WLM dwarf irregular galaxy and a sample of other dwarfs from the literature, we identify a correlation such that more rotationally supported dwarf galaxies show typically flatter radial metallicity profiles. In the context of tidally induced transformations of rotating dwarf irregulars into dispersion supported dwarf spheroidals, tidal stripping should preserve an initially flat metallicity profile - therefore this correlation may provide additional evidence that ram pressure is required for environmental transformations in the Local Group.

Key words. galaxies: dwarfs – galaxies: evolution

1. Introduction

Within the Local Group, ultra-faint dwarfs (UFDs) and the dwarf spheroidals (dSphs) are found preferentially within the virial radius of the Milky Way (MW) or M31, whereas dwarf irregulars (dIrrs) and the transition type dwarfs are located at larger distances (McConnachie et al. 2012). The dSphs residing in the high density environs tend to be without significant reservoirs of neutral gas, and show in-

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ternal stellar kinematics which are preferentially dispersion supported (e.g., Battaglia et al. 2006). By contrast, the dIrrs are rotationally supported with substantial gas fractions, suggesting that environmental processing via tidal stripping (which can alter stellar kinematics) or ram pressure (which acts to remove loosely bound gas) may be responsible for the observed morphology-density relation in the Local Group (Grebel et al. 2003)

Indeed several works (Mayer et al. 2001; Kazantzidis et al. 2011) have successfully reproduced the observed low angular momentum content of present day dSphs in simulations where tidal effects work to transform a rotating gas rich progenitor into a dSph. These simulations typically assumed an idealized thin, strongly rotating disky progenitor system.

Until recently (Leaman et al. 2009; Kirby et al. 2012), the *stellar* kinematics and abundances of old stars in *isolated* dIrrs were not well known. Spectroscopic studies of the stellar component in isolated dwarf galaxies are inherently difficult given the faint magnitudes ($V \sim 23$) of even the brightest stars. However galaxies such as VV 124 and WLM have been relatively isolated gravitationally for much of their life, and therefore represent an interesting test of what impact secular internal processes can impart on the galaxy's stellar populations. Importantly they also represent examples which may be more realistic for comparison to simulations of isolated dwarf galaxy evolution.

In Leaman et al. (2012) we showed that despite its isolation from the MW and M31 presently and through the last 10 Gyr, the WLM dIrr shows an intrinsically thick, and dynamically hot stellar component. Specifically, the ratio of rotation to pressure support in the stellar kinematics (V/σ) was found to be close to unity - roughly one sixth that of its strongly rotating gaseous component. Whether such a dynamically hot progenitor system falling into the MW still resembles a dSph after tidal processing is an interesting question, and in our follow up study we attempted to place joint constraints on the relative strength of tides and ram pressure by studying the comparative angular momentum and radial metallicity profiles of dwarf galaxies in the Local Group with high quality spectroscopic abundances.

2. Observations and results

The spectroscopic data of red giant branch (RGB) stars in WLM were obtained using the FORS2 spectrograph at VLT and the DEIMOS spectrograph on Keck. Stars were chosen from colour magnitude diagrams of WLM to be consistent with the location of the upper RGB, and importantly also were selected to span a significant radii within the galaxy in order to probe kinematic and chemical properties at large radii in the galaxy.

Abundances were derived using the near infrared calcium triplet (CaT) lines ($\lambda \sim 8600$Å) using the new recalibration from Starkenburg et al. (2010) to ensure a robust estimate of [Fe/H] from the CaT equivalent widths. Radial velocities were computed via cross correlation with a library of template spectra. Due to its extreme distance (nearly 1 Mpc from both the MW and M31 currently) nearly 8 hours of exposure time was needed per mask in order to get suitable signal to noise ($15 - 30$Å^{-1}) in the spectra.

The final sample included 180 RGB stars with well measured radial velocities, of which 126 had high enough signal to noise to also allow for individual measurements of [Fe/H]. The final uncertainties on the stellar velocities were on average $\sim$ 6 km s^{-1}, and the uncertainty on [Fe/H] was on average $\sim$ 0.25 dex. Details of the observations, sample selection, data reduction, and spectral analysis can be found in Leaman et al. (2009, 2012, 2013).

To compare the stellar kinematics and metallicity to other dwarf galaxies in the Local Group, we selected dwarfs from the literature which had statistically large samples of metallicity and velocities. We required that the stars in the dwarf galaxies spanned out to at least 75% of the tidal radius, and had derived [Fe/H] values done via robust (either recalibrated CaT calibrations, or spectral synthesis) measurement techniques. The final sample of galaxies included 6 dSphs (Fornax; Battaglia et al. 2006, Sculptor; Tolstoy et al. 2004, Sextans; Battaglia et al. 2011, Carina;

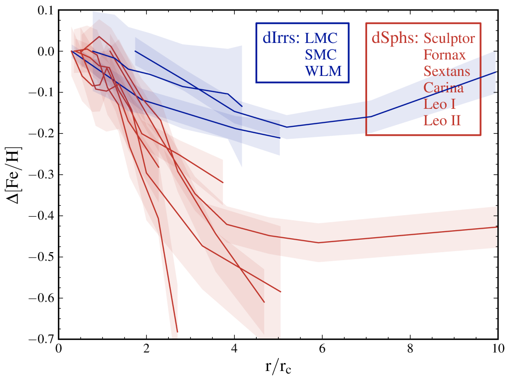

Fig. 1. Metallicity as a function of normalized radius in the sample of dIrrs and dSphs. Lines represent the running mean of metallicity from hundreds of individual stars with [Fe/H] measurements in each galaxy. The galaxies have been normalized to the central metallicity. From Leaman et al. (2013), reproduced with permissions.

Koch et al. 2006, and Leo I and II Kirby et al. 2010) 3 dIrrs (WLM; Leaman et al. 2009, 2012, 2013, the LMC; Cole et al. 2005; Pompeia et al. 2008; Carrera et al. 2008b, and the SMC; Carrera et al. 2008a; Parisi et al. 2010). To this we also added the large spectroscopic data of the 3 Local Group dwarf ellipticals (dEs) NGC 147, 185 and 205 from Geha et al. (2006, 2010).

2.1. Kinematic and metallicity trends in the dwarf galaxies

With the sample of dwarf galaxy abundances and kinematics, it was possible to compare and contrast the properties of not only dSphs and dIrrs, but isolated and near-by dIrrs (WLM, the Magellanic Clouds), and galaxies of similar mass but with different neutral gas content (dIrrs, dEs).

The metallicity distribution functions (MDFs) of the galaxies revealed that despite differences in isolation, gas fraction, or other factors, to first order the *average* metallicity is set by the luminosity or total mass of the galaxy. So despite having different kinematics and gas content, the MDF of the isolated dIrr WLM, shows nearly the same range of metallicity in its MDF (with stars as metal poor as [Fe/H]= -2.9 dex) as the Fornax dSph. That the mean metallicity is determined by the mass irregardless of gas content, has also been illustrated in updated mass-metallicity relations for Local Group dwarfs in Kirby et al. (2013).

While the global metallicity properties of an isolated dwarf irregular like WLM is very similar to dSphs of similar mass, we find differences in the *spatial* distribution of metals within WLM and the galaxies in the literature we consider. Figure 1 illustrates that the dIrr galaxies WLM, LMC and SMC, show comparably flatter metallicity gradients than the 6 dSphs in our sample. There are obvious differences in morphology and gas content between the dIrrs and dSphs, as well as differences in their dynamical structure.

Simulations by Schroyen et al. (2011) found that angular momentum could modulate the final radial metallicity distribution in dwarf galaxies in their simulations. In this scenario, angular momentum prevents the gas from funneling to the center of the the galaxy, thereby resulting in star formation (and chemical enrichment) which is more uniformly spread over the galaxies extent. To test this idea, we show in Figure 2 the strength of the radial metallicity gradient versus the angular momentum (ratio of rotational to dispersion support; V/σ) of the stellar populations in the dwarf galaxies we consider. As both the metallicity gradient and V/σ are quantities which change with radius, we show the range of the values over the full radial extent of data in a given dwarf galaxy.

There is a tendency for the high angular momentum dIrrs and dEs to show flatter radial metallicity profiles compared to the dispersion supported dSphs. While this would tend to support the simulation results of Schroyen et al. (2011) that angular momentum may set the radial metallicity profile, it should also be noted that these high angular momentum galaxies are also the ones with more gas, are more massive, and typically have different star formation histories. Therefore more work needs to be done to isolate which parameter (SFH, mass, angular momentum) is the strongest mediator of the final radial metallicity profile in a galaxy.

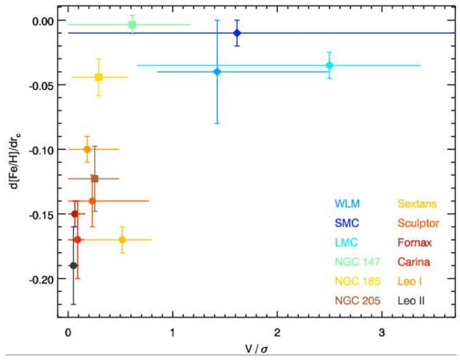

Fig. 2. Angular momentum (ratio of rotation to pressure support in the stellar component; V/σ) versus radial metallicity gradient strength for the dwarfs considered in this sample. Error bars represent the range of the two quantities spanned as a function of radius in a given galaxy. From Leaman et al. (2013), reproduced with permissions.

2.2. Implications for environmental processing

Regardless of the mechanism responsible for setting the radial gradient strength, the results of Figure 2 have important implications for environmental processing, and in particular the tidally driven transformation of a dIrr into a dSph. While the properties of a dSph progenitor galaxy are not known, they are typically assumed to be rotationally supported dIrr analogues. If the radial metallicity gradient and angular momentum correlations in Figure 2 are in fact caused by the latter parameter, then these dSph progenitors may also be expected to have flat metallicity gradients initially.

While tidal harassment of such systems easily can transform the kinematics into a low angular momentum dSph, it would be difficult to imagine that a progenitor with an initially flat metallicity gradient ends up with a significantly steeper gradient if only tidal stripping is acting. In such a case stars in the outer regions would be remove, and stellar orbits mixed, with simulations indicating (Sales et al. 2010) that the gradient strength would be flattened or preserved.

Therefore this correlation in Figure 2 may provide a hint that ram pressure is needed in conjunction with tidal stripping in order to jointly reproduce the stellar kinematics and radial metallicity gradients in Local Group dSphs. In particular such a result may place constraints on the efficiency of ram pressure, as it could require that star formation continues while the gas is removed slowly in the outer regions of the dwarf galaxy. This slow contraction of the star forming disk could produce the necessary steep radial metallicity gradient in the dSphs.

3. Conclusions

Using spectroscopic metallicities and velocities from individual RGB stars in a sample of Local Group dwarf galaxies we present a comparison of the angular momentum and spatial variations in metallicity in the galaxies. While the average metallicity properties appear to be driven simply by the total mass of the galaxy, irrespective of morphological type (dIrr or dSph), the spatial distribution of metals show differences, with the dIrrs showing shallower metallicity gradients. Specifically, we show that there is a correlation between the metallicity gradient strength and the level of rotational support in a galaxy. While other factors such as variations in SFH may play a role, such a correlation may place constraints on the relative strength of ram pressure and tides in transforming a rotating gas rich dwarf into a dispersion supported dSph with a steep metallicity gradient. Future simulations incorporating both ram pressure and tidal stripping while tracking the stellar metallicity would be very informative in this context.

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