WHY GALAXIES CARE ABOUT AGB STARS II:
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The Local Group: Inventory and History

E. Tolstoy

Kapteyn Astronomical Institute, University of Groningen, the Netherlands

Abstract. An overview is presented of what we know about the Local Group of galaxies, primarily from optical imaging and spectroscopy. AGB stars are on the whole a very sparse and unrepresentative stellar population in most Local Group galaxies. However, more detailed studies of star formation histories and chemical evolution properties of populations, such as main sequence dwarf stars and red giant branch stars, allow a better understanding of the evolutionary context in which AGB stars can be observed. There are a variety of galaxy types in the Local Group which range from predominantly metal-poor (e.g. Leo A) to metal-rich (e.g. M 32). Dwarf galaxies are the most numerous type of galaxy in the Local Group and provide the opportunity to study a relatively simple, typically metal-poor, environment that is likely similar to the conditions in the early history of all galaxies. The range of star formation histories, peak star formation rates, and metallicities should provide enough information to properly calibrate observations of AGB stars in more distant systems, and indeed in integrated spectra. Here I summarise what we know about the star formation histories of nearby galaxies and their chemical evolution histories and then attempt to make a connection to their AGB star properties.

1. Introduction

Within the Local Universe galaxies can be studied in great detail, star by star. The method of Colour-Magnitude Diagram (CMD) synthesis is well established, at optical wavelengths, as the most accurate way to determine the detailed star formation history of galaxies going back to the earliest times (e.g. Tolstoy, Hill, & Tosi 2009). This approach has benefited enormously from the exceptional data sets that wide-field CCD imagers on the ground and the *Hubble Space Telescope* can provide. Spectroscopic studies using large ground-based telescopes have allowed the determination of abundances and kinematics for significant samples of red giant branch (RGB) stars and also more massive O, B and A stars in several nearby galaxies (e.g. Tolstoy et al. 2009, and references therein). These studies have shown directly how properties can vary spatially and temporally, and how this information can give important constraints to theories of galaxy formation and evolution.

Dwarf galaxies are commonly used as probes of a simple "single cell" star-forming environment. They cover a range of mass and metallicity and are considered to be representative of how galaxies in the early universe may have looked. A working definition of dwarf galaxies includes all galaxies that are fainter than $M_B \leq -16$ ($M_V \leq -17$) and more spatially extended than globular clusters (e.g. Tammann 1994); see Figures 1 & 2. Although these limits were not physically defined, they are broadly consistent with the limit of mass and concentration at which gas outflows are likely to start to signifi-

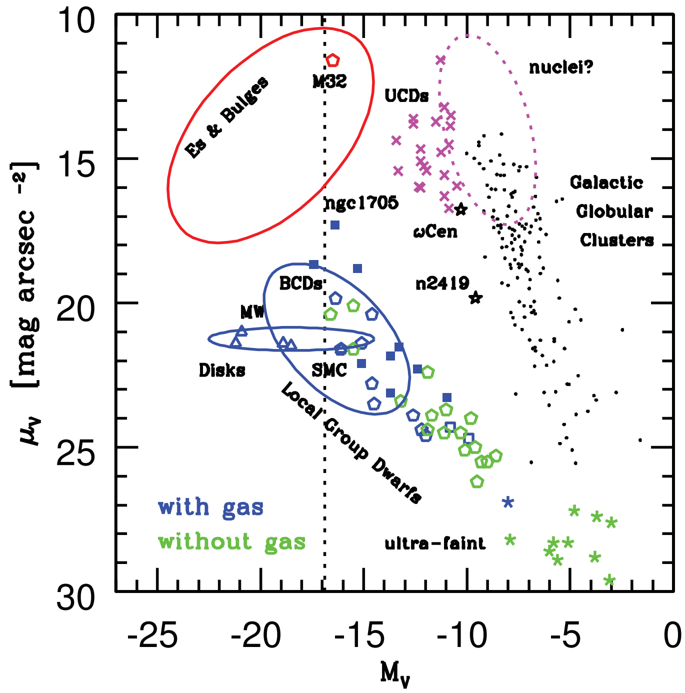

Figure 1. The relationship between the structural properties (absolute magnitude M_V and central surface brightness μ_V) for a range of galaxy types. The dotted line is the classical maximum luminosity of the dwarf galaxy class, from Tammann (1994). Local Group galaxies are plotted as open pentagons, with the colour depending upon their gas content. The Sloan-discovered ultra-faint systems are plotted as star symbols. Blue Compact Dwarf galaxies are squares, Ultra-compact systems are crosses, and Galactic globular clusters are dots. See Tolstoy et al. (2009) and Binggeli (1994) for more details.

cantly effect the baryonic mass of a galaxy. This includes a number of different types: early-type dwarf spheroidals (dSphs); late-type star-forming dwarf irregulars (dIs); the recently discovered very low surface brightness, ultra-faint dwarfs (uFd); and the centrally concentrated actively star-forming blue compact dwarf galaxies (BCDs). The newly discovered, even more extreme, so-called ultra-compact dwarfs (UCDs) are identified as dwarf galaxies from spectra but are of a similar compactness to globular clusters (see purple crosses in Figure 2). The dIs, BCDs, dSphs, late-type and spheroidal galaxies tend to overlap with each other in global properties in Figures 1 & 2. These overlapping properties of early and late-type dwarfs have long been assumed to be convincing evidence that early-type dwarfs are late-type systems that have been stripped of, or otherwise used up, their gas (e.g. Kormendy 1985).

Thus, as with larger systems, the global properties of dwarf galaxies correlate closely with luminosity, half-light radius and surface brightness, over a large range. Dwarf galaxies thus allow us to study specific aspects of galaxy formation and evolution on a small scale.

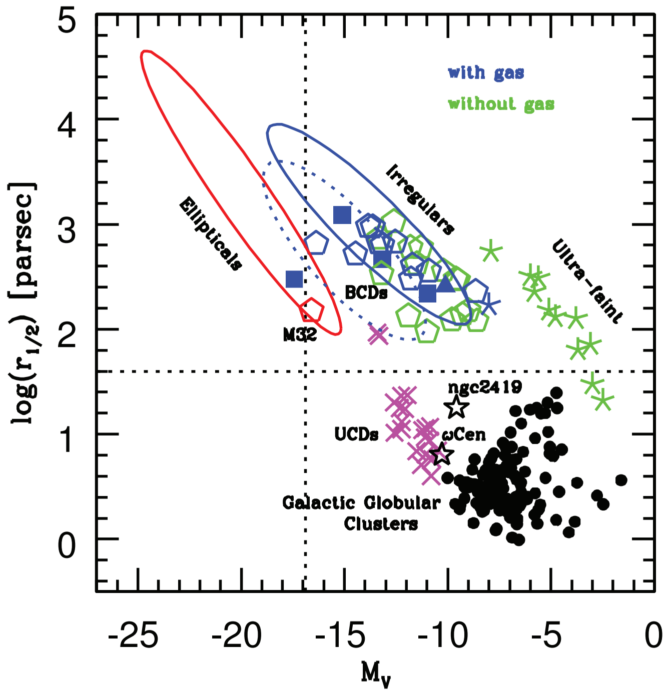

Figure 2. The relationship between the structural properties (absolute magnitude M_V and half-light radius r_h) for a range of galaxy types. The dotted lines are the classical maximum luminosity of the dwarf galaxy class, and the minimum spatial extent, from Tammann (1994). The symbols are the same as in Figure 1. See Tolstoy et al. (2009) and Belokurov et al. (2007) for more details.

2. Optical Imaging: Star Formation Histories

There are significant difficulties in obtaining and accurately interpreting the CMDs of galaxies at distances beyond the Local Group; see Figure 3. Since it is only possible to observe galaxies star by star in the very nearby Universe (predominantly within the Local Group), there are selection effects that will almost certainly bias our conclusions from these types of studies. The main uncertainty is due to the fact that we can only study the star formation history (SFH) back to the earliest times within the halo of the Milky Way and in very nearby galaxies; see Figure 3 and also Cignoni & Tosi (2010). These galaxies have most likely suffered significant evolutionary effects, as suggested by the morphology-density relation (e.g. Mateo 2008). It will be hard to remove this bias in our observations until a significant leap in sensitivity and resolution can be made to allow us to look to greater distances with comparable accuracy (e.g., a large space telescope or an extremely large ground-based telescope working near to its diffraction limit).

Main sequence star luminosities have a clear age dependence, and are thus by far the most accurate age indicators of resolved stellar populations as part of the full fitting of the colour-magnitude diagram (e.g. Aparicio & Gallart 2004). The fact that a stellar

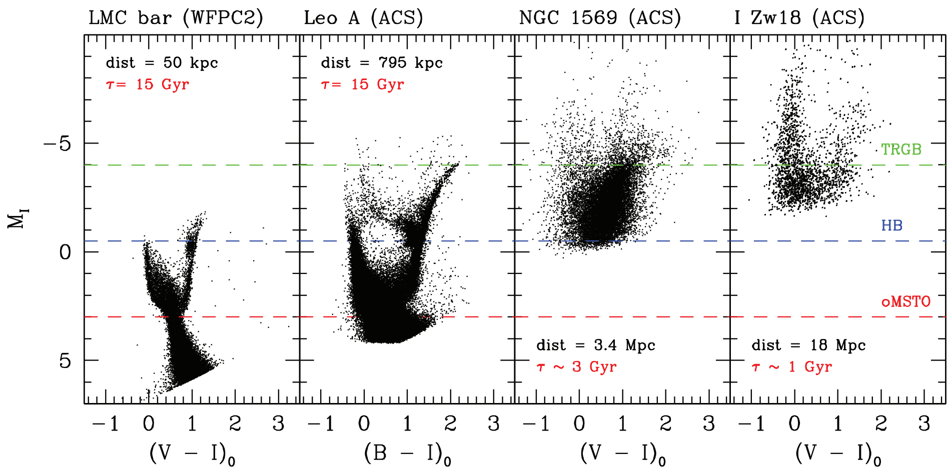

Figure 3. The effect of distance on the resolution of individual stars and on the corresponding look-back time, τ, of the star formation history. The CMDs are in absolute magnitude (M_I) vs. wideband colour, all observed with long exposure times by HST and photometered with the same techniques, but at different distances. *Left to right*: The LMC bar (50 kpc: Smecker-Hane et al. 2002); Leo A (795 kpc: Cole et al. 2007); NGC 1569 (3.4 Mpc: Grocholski et al. 2008; McQuinn et al. 2010); I Zw18 (18 Mpc: Aloisi et al. 2007).

population is resolved down to the oldest main-sequence turnoffs ($M_I \sim 3$) means that the luminosity bias that is so apparent in integrated light studies can be largely removed. A significant amount of effort has gone into this kind of work from both large-format CCD observations of very nearby galaxies (e.g. Hurley-Keller, Mateo, & Nemec 1998; Harris & Zaritsky 2009, de Boer et al., in prep.), which are large on the sky, and also from deep HST observations for more distant systems (e.g. Skillman et al. 2003; Cole et al. 2007; Monelli et al. 2010) .

Because the number and range of galaxy types in the Local Group is strongly biased to dwarf galaxies, this is the main type of galaxy studied in such detail. Dwarf galaxies are also more straightforward to observe since a large fraction of the system can be included in "one shot," even with HST. There have been numerous detailed studies of individual dwarf galaxies (e.g. Tolstoy et al. 2009, and references therein). We also mention (1) a project to treat uniformly a large set of archival HST WFPC2 observations of Local Group galaxies, to create accurate star formation histories in a consistent manner (Dolphin et al. 2005; Holtzman et al. 2006); (2) challenging studies of compact systems with extreme crowding such as M 32 (Monachesi et al. 2011), backed up by RR Lyr studies (Fiorentino et al. 2010); and (3) deep observations of small HST fields in the M 31 halo (e.g. Brown et al. 2003) and LMC (e.g. Holtzman et al. 1999; Smecker-Hane et al. 2002).

To look at currently more active star forming systems, for example Blue Compact Dwarfs, we need to look beyond the Local Group (e.g. NGC 1569 at 3.4 Mpc: see Fig. 3 and Grocholski et al. 2008; McQuinn et al. 2010). With increasing distance, it becomes harder to detect anything other than bright stars, and the photometric errors tend to smear out the features of the CMD. Going from left to right in Figure 3 we

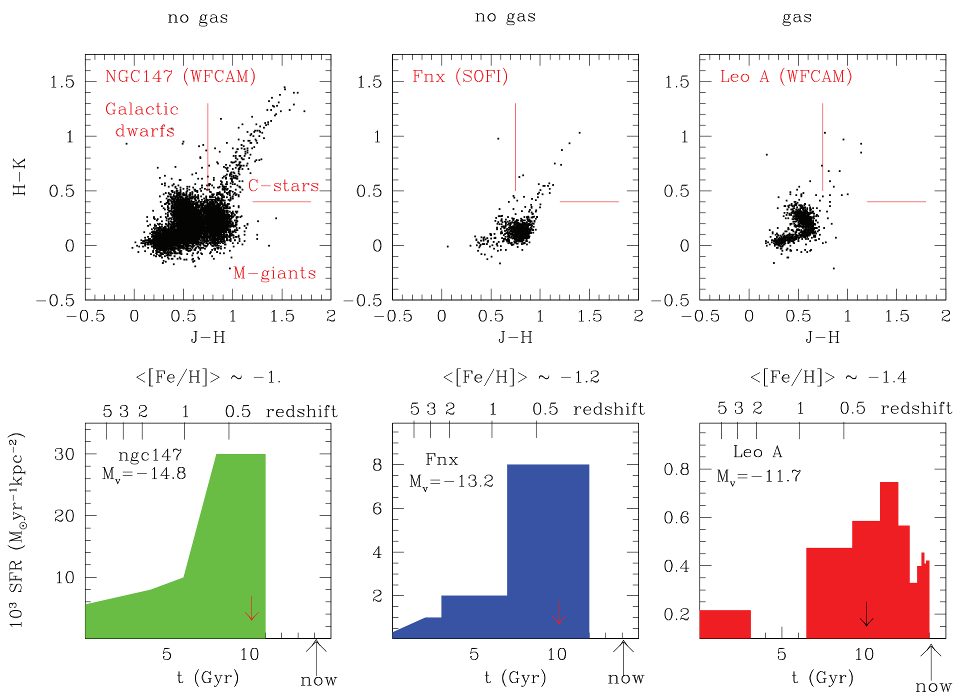

Figure 4. In the top panels are the infrared colour-colour diagrams for three dwarf galaxies: NGC 147 (WFCAM data, over 0.8 sq deg., Irwin et al. in prep); Fornax dSph (SOFI data, over 0.1 sq deg. Gullieuszik et al. 2007); and Leo A (WFCAM data, over 0.8 sq deg., Irwin et al. in prep). The different stellar evolution phases that are delineated in accurate colour-colour diagram sequences are labeled in the leftmost diagram. The C stars (or AGB stars) and the M giants are in the galaxy itself. The rest of the stars are predominantly Galactic dwarf stars. In the lower panels are the corresponding star formation histories for the same three galaxies, from Dolphin et al. (2005, NGC 147); Tolstoy et al. (2001, Fnx); and Cole et al. (2007, Leo A).

see that the features in the CMDs become less well defined. This is mostly due to photometric errors due to the increasing faintness of the stars, but also to the related effect of increasing crowding, which makes it difficult to accurately disentangle the measurements of (faint) individual stars from their neighbours. Often there are a large number of stars above the tip of the RGB in BCD galaxies (e.g. NGC 1569). These may be just the effects of crowding, but they might reflect the presence of AGB stars, indicating that a significant amount of star formation has occurred a few Gyr ago.

Of course this difficulty in detecting faint (blue) main sequence turnoff stars may have an obvious alternative in the presence of bright red AGB stars in images of galaxies extending to distances well beyond the Local Group (e.g. Girardi et al. 2010). However, without a better calibration of the effects of age and metallicity on the AGB population it is hard to quantify their presence in terms of an accurate star formation rate at a given time (see also VII Zw403: Lynds et al. 1998). The CMDs in Figure 3 do not always give a good overview of the very red stars such as AGB stars in these galaxies. This is because they do not always stand out very clearly in optical CMDs. What is really needed are infrared observations of this population, and colour-colour diagrams can be especially useful (e.g., Cioni & Habing 2003; Gullieuszik et al. 2007); see Figure 4. These populations can then be calibrated in terms of ages and metallicities coming from optical imaging and spectroscopy.

In Fig. 4 we look at the star formation histories and also the number of AGB stars (as seen in IR colour-colour diagrams) in three nearby galaxies with a range of luminosity (from $M_v = -14.8$ to -11.7) and also a range of mean metallicity ([Fe/H] $= -1$ to -1.4) at the time the AGB stars were born. These three galaxies (NGC 147, Fornax dSph, and Leo A) were chosen because they have very similar star formation histories, with a peak around 3−5 Gyr. In each case the absolute rate at the peak is quite different. The more luminous the galaxy, the higher the peak star formation rate. But they all had their peak activities at a similar period in the past. The number of C stars (AGB stars) that can be seen in the colour-colour diagrams varies by a larger amount than the SFR differences might imply, especially in the case of NGC 147. This might suggest that an important factor is also the metallicity at which the stars were forming 3−5 Gyr ago (these are also labelled in Fig. 4). The C stars in Leo A still need to be carefully studied. These would likely be the most metal-poor C stars in the Local Group, if confirmed, given that the present-day H II region abundance is a mere 3% of solar (van Zee, Skillman, & Haynes 2006). The stars in the C-star region of the colour-colour diagram for Leo A look more untidy than the usual AGB sequence, and may well be the result of confusion or young (massive) stars in H II regions.

Considering the SFHs of dwarf galaxies as a group, there is no discernible trend in either duration or average age of stellar population with either mass, luminosity, or rotation; they seem to reach a similar luminosity by distinct routes (e.g. Skillman 2007). The only effect seems to be that when a galaxy forms stars, everything else being equal, the maximum rate seems proportional to the mass of the galaxy, that is to the total number of stars formed, but not when they formed. How the number of evolved stars (e.g., carbon stars, or E-AGB stars) fits into SFH has not yet been clearly quantified. The number of AGB stars should be studied for a range of galaxies using the accurate SFHs from deep optical data where available to better understand if it is possible to disentangle the effects of age, metallicity and small number statistics in the interpretation of their properties.

3. Optical Spectroscopy: Abundance Properties

For most galaxies in the Local Group it is possible to take spectra of large samples of individual RGB stars at intermediate resolution. This allows the observation of well calibrated, simple-to-use metallicity indicators, such as the Ca II triplet (e.g., Starkenburg et al. 2010; Battaglia et al. 2008b). These measurements allow a detailed measurement of the metallicity distribution function from many hundreds and sometimes even thousands of individual stars. The kinematic properties of galaxies can also be disentangled with these spectra (e.g., Battaglia et al. 2008a), as well as any connection between distinct kinematic components and metallicity. This leads to accurate mass modelling of individual galaxies and also to the discovery of distinct kinematic components, even in small dwarf galaxies, and sometimes also rotation (e.g. Lewis et al. 2007; Fraternali et al. 2009).

In the nearest systems (i.e., mostly dwarf galaxies, but also the Magellanic Clouds) it is possible to take high-resolution spectra of individual RGB stars. This allows

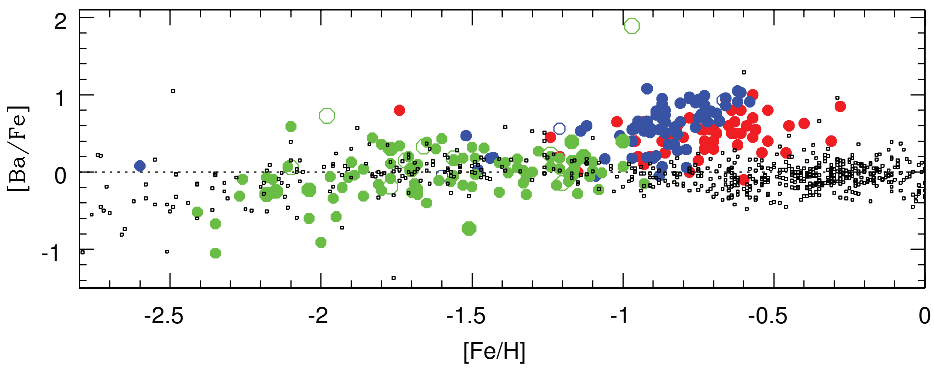

Figure 5. Abundances in individual red giant branch stars from high-resolution studies. Scupltor dSph (green) – solid circles: Hill et al., in prep.; open circles: Shetrone et al. (2003); Fornax dSph (blue) – solid circles: Letarte et al. (2010); open circles: Shetrone et al. (2003); Large Magellanic Cloud (red) – circles: Pompéia et al. (2008). The small black squares are Galactic observations (from compilation of Venn et al. 2004).

us to measure detailed abundances of numerous chemical elements. The most commonly observed are the α–elements (e.g., O, Ca, Mg, Ti), but also heavy elements such as r-process elements (e.g., Eu), iron-peak elements (e.g., Mn, Cr, Fe, Ni) and also s-process elements (e.g., Ba). The abundances of these elements in RGB stars allow us to probe their levels over the entire star formation history that occurred > 1 Gyr ago. This allows us to follow which enrichment processes dominate at different epochs in the galaxy, and thus their time-scale, and how they affect and are affected by the presence or absence of other elements.

The most important elements for tracing the effect of AGB stars and their pollution of the ISM out of which subsequent generations of stars are made are the s-process elements. Figure 5 shows the detailed abundances of barium compared to iron, [Ba/Fe], based on high-resolution spectroscopic observations of individual RGB stars in the Sculptor dSph, the Fornax dSph, and the Large Magellanic Cloud, compared to RGB stars in the Galactic disk and halo. Barium is of particular interest because at these [Fe/H] values it is produced almost entirely by the s-process. This also makes it a good indicator of how many potential s-process sources there have been and when they were most productive. Fig. 5 shows that both the LMC and Fornax have significantly enhanced [Ba/Fe] compared to the Galaxy at $[Fe/H] > -1$. It seems that this enhancement only starts at $[Fe/H] \sim -1$. Sculptor does not show the same effect, presumably because it never reached a high enough metallicity before all star formation stopped. It might also be because Sculptor stopped forming stars before the feedback of s-process elements from AGB stars became important to the chemical enrichment.

In Figure 6 we consider the evolution of [Fe/H] in the same galaxies as shown in Figure 4, i.e., Sculptor dSph, Fornax dSph, and the Large Magellanic Cloud. In Fig. 4 we show colour-colour diagrams based on 2MASS data for each of the galaxies. The physical region sampled is the same for Sculptor and Fornax (1°, which is about the distance to the tidal radius). This region is a smaller fraction of the whole galaxy for the LMC. Clearly the LMC is a larger, more luminous galaxy (with a higher peak star formation rate) than the other two, and the LMC also contains many more AGB stars.

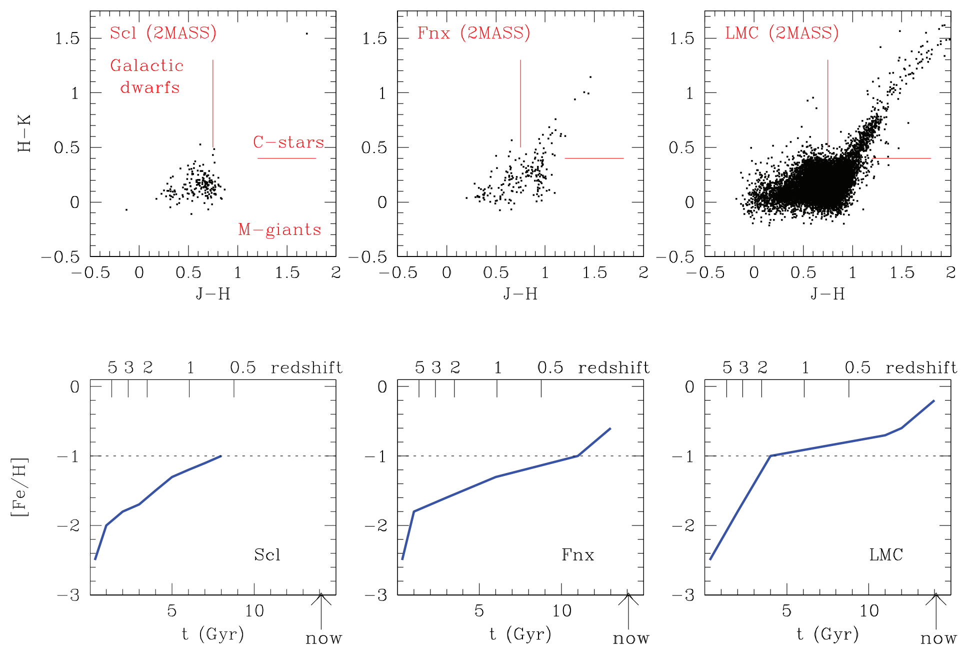

Figure 6. For the same galaxies as shown in Fig. 5, the metallicity-age relations are shown in the lower panels, and the upper panels show the colour-colour diagrams which clearly show the numbers of AGB (C stars) present. The age-metallicity relations come from de Boer et al. (in prep) for Sculptor, Battaglia et al. (2006) for Fornax, and Pagel & Tautvaisiene (1998) and Hill et al. (2000) for the LMC. The infrared data are from 2MASS (only those stars with AAA quality flags), in a region that corresponds to the tidal radius of Scl and Fnx, and within the central 1° of the LMC.

The variation in the number of AGB stars seen in these nearby galaxies may be due to the different masses, sizes and/or luminosities of the systems, but there is also likely to be a significant effect due to metallicity. It can be seen that a galaxy that never forms stars with [Fe/H] > -1 (e.g. Sculptor, see Fig. 6) also appears to contain no AGB C stars, and there is no sign of enrichment by these stars during its star formation history (Fig. 5). Of course Sculptor also stopped forming stars around 6 Gyr ago, and for several Gyr before this it formed stars at a very low rate (see de Boer et al., in prep.), and it might be a case of low number statistics. But Leo A is a galaxy with a similar luminosity to Sculptor, and a current metallicity (from H II region spectroscopy) which is similar to the average metallicity found in Sculptor. Leo A also formed most of its stars over the last 5 Gyr and yet has very few, if any, AGB stars (see Fig. 4).

4. Conclusions

It is clear the that AGB stars can play a very significant role in the chemical evolution of a galaxy, especially a dwarf galaxy. A dwarf galaxy with an extended star formation history will likely be highly sensitive to the chemical enrichment created by the relatively slow and steady stellar winds from AGB stars. In small galaxies, supernovae may drive mass and metals entirely out of the galaxy, but stellar winds from AGB stars probably will not. The effect of AGB stars is likely to depend on the time-scale over which star formation occurred. The products of these stellar winds must be returned to the ISM on a time frame consistent with the subsequent star formation episodes in a galaxy to have an impact on its chemical evolution. From the lack of AGB stars in very metal poor systems, it also seems likely that [Fe/H] plays a role in the evolution of AGB star populations. It seems to be more difficult to produce metal-poor AGB stars, and also to measure any effect in the abundance ratios that may come from them.

In this review I have just touched upon the connections that can be made between the AGB star properties of nearby galaxies and their star formation histories and metallicities. These results are likely to be placed on a much more quantitative basis in the coming years as more wide-field near-IR and optical imaging and spectroscopic surveys are carried out for both nearby and more distant galaxies. It is clear that to sort out the complex and intertwined effects of star formation, stellar winds, supernovae explosions and their effect on the ISM we need to use information from a variety of sources that are sensitive to different time-scales and physical processes. This means that we need to combine information from optical imaging (SFHs) and spectroscopy (abundances) with IR imaging and spectroscopy to get the full story.

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Discussion

Sloan: If the star formation history does not depend on any intrinsic property of a galaxy, does it follow that it depends instead on the history of interactions with other galaxies?

Tolstoy: Star formation is stochastic to begin with. Even in isolated galaxies, star formation history is variable over time. There are cases where it is likely that an encounter with a large galaxy stripped gas from dwarf galaxies (e.g., Sculptor dSph) but on the whole dwarf galaxies are close to the edge of star formation liability, below Kennicutt threshold.

Feast: Where one has dwarf galaxies having same absolute mass, e.g. the three galaxies you compared, but different histories, is there a correlation of properties with mass/light ratio?

Tolstoy: This is a little hard to be sure. It is not clear that any of the galaxies is in any kind of equilibrium because the mass is so hard to measure. Leo A is gas rich, and the mass is determined from HI rotation ($\sim$ 5km/s); Sculptor is gas poor, and the mass is determined from stellar velocity disperisons. It is not clear whether these can be easily compared, or that either is reliable. Some people say fainter dwarf galaxies are more dark matter dominated than brighter. But this is rather doubtful given increasingly uncertain reliability of equilibrium assumption going to fainter systems.