Chemical Signatures in Dwarf Galaxies

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Chemical signatures in dwarf galaxies describe the examination of specific elemental abundance ratios to investigate the formation and evolution of dwarf galaxies, particularly when compared with the variety of stellar populations in the Galaxy. Abundance ratios can come from H II region emission lines, planetary nebulae, or supernova remnants, but mostly they come from stars. Since stars can live a very long time, for example, a 0.8 $M_\odot$ star born at the time of the Big Bang would only now be ascending the red giant branch, and, if, for the most part, its quiescent main sequence lifetime had been uneventful, then it is possible that the surface chemistry of stars actually still resembles their natal chemistry. Detailed abundances of stars in dwarf galaxies can be used to reconstruct their chemical evolution, which we now find to be distinct from any other component of the Galaxy, questioning the assertion that dwarf galaxies like these built up the Galaxy. Potential solutions to reconciling dwarf galaxy abundances and Galaxy formation models include the timescale for significant merging and the possibility for uncovering different stellar populations in the new ultra-faint dwarfs.

The Local Group

The Local Group seems to be more crowded now than it was ten years ago. Although we knew about the three large spiral galaxies (the Milky Way – hereafter MWG, M31, and M33), and we knew about dwarf galaxies with smaller masses (the Magellanic Clouds and other smaller satellites of the MWG and M31, as well as the isolated dwarfs), what we did not know was that there were also extremely faint and low mass dwarf galaxies lurking within our midst. These galaxies, mostly discovered in the Sloan Digital Sky Survey (SDSS; e.g., Belokurov et al., 2007) data, have properties that are only now being uncovered (see presentations at *http://www.mpa-garching.mpg.de/mpa/conferences/garcon08*).

How these different types of galaxies are related to one another raises an interesting series of questions. Are dwarf galaxies related to protogalactic fragments, the low mass systems that formed in a Λ Cold Dark Matter (LCDM) Universe that later merged to build up the large spirals that we see today? Are the dwarf spheroidal and Sloan galaxies that we find in the halo of the MWG related to the gas-rich dwarf irregular and gas-poor transition galaxies that are further away and often isolated? One way to address these questions is to search for similarities in the chemical patterns of the stars in these galaxies.

The build-up of the chemical elements is unique to each galaxy, depending on their mass, initial conditions, star formation histories and gas infall and outflow properties. Since dwarf galaxies do not exchange gas with one another (other than through major merging events that leave only one galaxy remaining), then the chemical evolution of each dwarf galaxy is independent. So how does the chemistry in each dwarf galaxy differ, or are they all the same? Looking at the stars in the MWG suggests that they are not all going to be the same.

Chemical signatures: from the Milky Way to Local Group (dwarf) galaxies

The first studies of the chemical evolution of the stars in a galaxy occurred in the 1970s by Beatrice Tinsley and collaborators (e.g., Tinsley, 1979). In these studies, they collected the detailed elemental abundances in metal-poor stars in the Galaxy and tried to model the build-up of the elements to the present day, assuming that the Galaxy formed from a monolithic collapse (Eggen, Lynden-Bell & Sandage, 1962). The achievements of these early models are impressive. Looking at Figures 3 and 6 from Tinsley (1979), an examination of the rise in s-process elements through the evolution of asymptotic giant branch (AGB) stars is not too different from the results of today's more sophisticated (and physically accurate) models.

Studies of the chemical abundances of stars in dwarf galaxies are more recent. Shetrone et al. (1998) determined the first detailed chemistries for stars in the Draco dwarf galaxy. Ironically, they were mainly interested in using the stars in Draco to address the pattern of deep mixing that is seen in red giant stars in globular clusters, but never in similar field stars in the Galaxy, but quickly realised the potential of this work for examining galaxy formation. Previous to Shetrone's work, elemental abundances were determined only for H II regions, planetary nebulae, and bright supergiants in the Magellanic Clouds (e.g., Olszewski et al., 1996). This can tell us about the end point of the chemical evolution of these galaxies, but not of the initial conditions, nor the intervening steps, because all of these objects are young. Some carbon abundances had been determined for stars in the Ursa Minor dwarf galaxy (Suntzeff, 1985), but no other elements were examined. It is impressive that we have gone from four lone stars in one dwarf galaxy to hundreds of stars in five dwarf galaxies in less than a decade, and with more stars and galaxies on the way.

We are into the decade of large samples of stars in other galaxies with detailed chemical abundance determinations. These datasets allow us to: (1) characterise a wider variety of stellar populations; (2) examine similarities and differences with respect to MWG stellar populations, as well as between the various dwarf galaxies; (3) constrain nucleosynthesis and stellar yields in the models; (4) examine supernova (SN) feedback and reionisation effects on the evolution of dwarf galaxies; (5) disentangle age and metallicity effects in the analysis of the red giant branch from colour-magnitude diagrams – which can still be a complicated procedure; and (6) couple metallicity and kinematic information to examine variations in time and location of star formation events, and/or galaxy interactions. Ultimately, all of these individual questions are important in making comparisons with the MWG stellar populations, testing galaxy formation scenarios and LCDM cosmology.

Chemical signatures in the Milky Way

There are five dwarf galaxies to date with detailed chemistries determined for a large sample of stars. These include the three dwarf spheroidal galaxies (Sculptor, Fornax and Carina), as well as two dwarf irregular galaxies (LMC and Sagittarius). Most of these abundance analyses have been from high resolution spectra taken at the VLT with the FLAMES and UVES spectrographs. Examination of the colour-magnitude diagrams for these five galaxies show that each has had a very different star formation history (e.g., Tolstoy et al., 2003; Smecker-Hane et al., 2002; Bellazzini et al., 2006). The simplest assumption is that they have had very different chemical evolution routes from one another as well. But, do any of them have a chemical history similar to any of the stellar populations in the Galaxy (e.g., halo, thin disc, retrograde stars, etc.)?

All the chemical elements are of interest in this examination, though some give more information than others. α-elements are particularly important when compared with iron group elements, because they have different nucleosynthetic sources: iron forms during the surface detonation of a white dwarf in a Type Ia supernova explosion; α-elements are those that form through α-captures during nucleosynthesis (i.e., the capture of a helium nucleus, e.g., oxygen, magnesium, silicon, calcium, during quiescent helium burning in the core of massive stars). Thus the alpha/iron ratio is similar to examining the yields from hydrostatic burning in massive stars versus those from explosive nucleosynthesis in low mass stars. Differences in the star formation history of a galaxy will show up as differences in the alpha/iron ratios.

Of course, the simplest interpretation of the alpha/iron ratios in stars can be complicated by SN feedback, gas infall, or other events in the evolution of a galaxy. Thankfully these additional processes can have a different influence on the abundances of other elements. Other elements worth examining include r-process elements (i.e., those that form through rapid neutron capture during Type II supernova collapse, e.g., europium, neodymium, gallium) and s-process elements (i.e., those that form through slow neutron capture during the thermal pulsing phases of an AGB star, e.g., yttrium, strontium, barium). The reason that the s-process and r-process elements are particularly useful is not only their different nucleosynthetic sites and timescales for enrichment, but also that the yields from these sites are metallicity dependent. Their dependence on metallicity (the seeds for these processes) makes the build up of these elements strongly coupled to the star formation history of the host galaxy, which builds up over a non-unique timescale. Thus, variations in star formation history, as well as variations in SN feedback or gas infall/outflow, can be probed with s-process/r-process element ratios and alpha/r-process ratios.

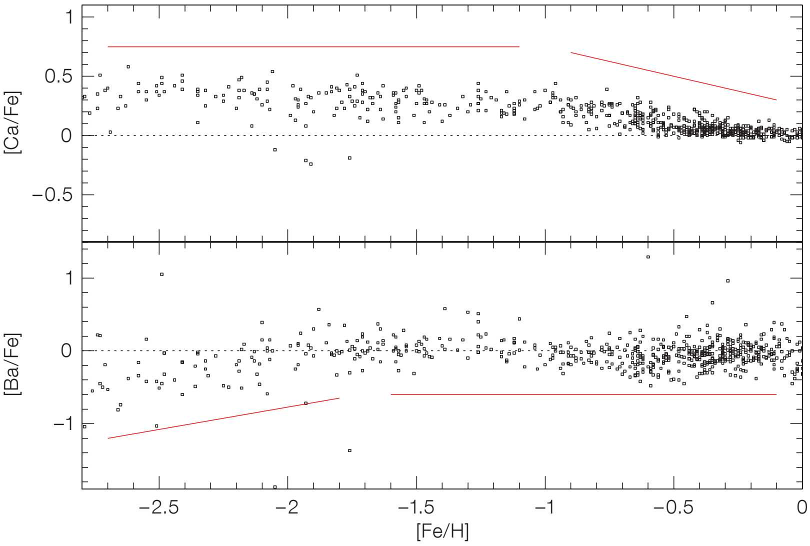


Figure 1. Comparison of the change in the calcium and barium abundances relative to changes in the iron abundances of stars in the Galaxy. The long red lines are a guide to the yields of these elements during the chemical evolution of the Galaxy. For [Ca/Fe] the high values at low [Fe/H] represent the yields from massive star nucleosynthesis and Type II supernovae, while the downward slope after [Fe/H] = –1.0 represents the contribution only to iron from low mass Type Ia supernovae. For [Ba/Fe], the rising line at low [Fe/H] values represents the increasing yield of barium over iron from Type II supernovae of higher metallicity, while the flat line after [Fe/H] = –1.8 represents the coincidentally similar yields of barium, from intermediate mass AGB stars, and iron, from low mass Type Ia supernovae.

In Figure 1, the abundances of calcium (α-element) and barium (r-process and s-process element) are compared to iron for stars in the Galaxy, as compiled by Venn et al. (2004). The element patterns for these two elements are not the same. When the iron abundance is quite low, then the calcium abundance does not quite scale in the same way, such that there appears to be an overabundance of calcium relative to the iron deficiency. Barium, however, is even more deficient than iron at low metallicities. These ratios are plotted with respect to the Sun (which is at [Fe/H] = 0, and on a logarithmic scale). Why do these elements have different patterns?

Calcium, as an α-element, forms in massive stars. The high calcium/iron ratio at low metallicities suggests that massive stars form both calcium and iron and deposit these elements back into the interstellar medium with the ratio seen on the plot. Eventually the low mass stars also evolve and explode as Type Ia supernovae. These events create iron-group elements without any calcium, causing the calcium/iron ratio to decrease (forming a 'knee' in Figure 1). Taken together, the suggestion is that the Galaxy was enriched to a metallicity 1/10th solar ([Fe/H] = –1.0; location of the knee) by massive stars alone, therefore rather quickly since massive stars have very short lifetimes (< 1 Gyr), and after this time the lower mass stars were able to contribute iron. This also means that the metallicity scale along the x-axis in Figure 1 is absolutely not linearly related to age! The first Gyr of our Galaxy's chemical evolution is represented by most of the figure, and the past 12 Gyr by a tiny portion on the righthand side.

Barium is an element that has contributions from both massive stars during Type II supernovae and rapid neutron capture, as well as intermediate mass stars during slow neutron capture happening in the AGB phase. That the barium/iron ratio rises at the lowest metallicities shows that Type II supernovae contribute less barium than iron, however as iron goes up, then more barium is made and the contribution of barium increases. At a metallicity near 1/50th solar ([Fe/H] = –1.8) then the barium/iron ratio is flat, implying that the yields of these elements are the same, but from what source? In the Galaxy, it appears to be a coincidence that the barium yield from the s-process in the AGB stars is similar to the iron yield from Type Ia supernovae (which contribute the iron at this metallicity).

Additionally, the position of the knee in the barium plot differs from that of the calcium plot in Figure 1 ([Fe/H] = –1.8 for barium/iron, rather than –1.0 for calcium/iron). Since AGB stars can include higher mass stars than Type Ia supernovae, then these stars will evolve and contribute their products at earlier times (or lower metallicities).

Chemical signatures in dwarf galaxies

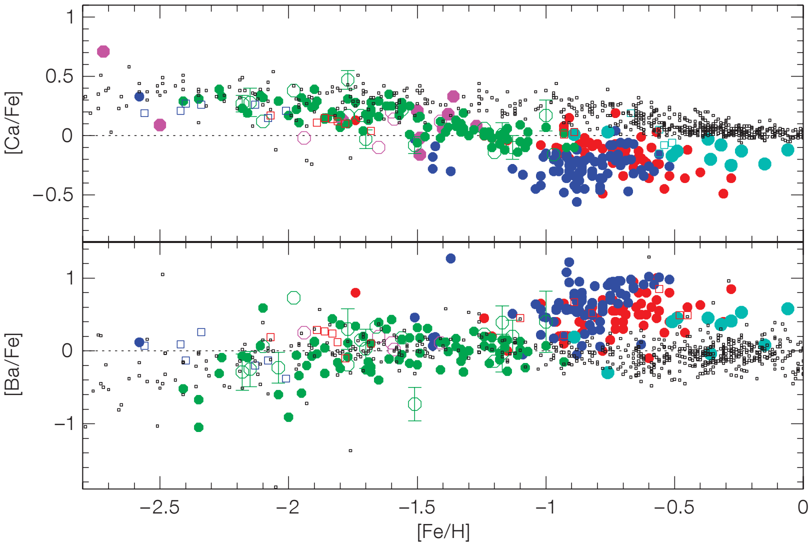
How do these abundance ratios, discussed in the MWG context, look in dwarf galaxies? Are they the same as in the MWG? We might expect the ratios to be the same if the MWG formed from ongoing merging of small dwarf galaxies to the present epoch. The past decade of work on the chemistry of stars in nearby dwarf galaxies has shown that this is not the case, and that dwarf galaxies have their own unique chemical patterns and chemical signatures.

In Figure 2, the calcium and barium abundances are shown in the five dwarf galaxies that have had their chemistries determined from large samples of stars. The LMC stars analysed by Pompéia et al. (2008; red) show lower calcium and higher barium abundances than similar metallicity stars in the Galaxy. Thus, the stars in the Galaxy do not resemble those in the LMC. The stars in the Galaxy sample are from the thick and thin disc, and it had been proposed that the discs of our Galaxy could have formed through the merger of an LMC-sized dwarf galaxy (e.g., Abadi et al., 2003). However, if that were true then the chemistry of this virtual galaxy must have been quite different from that of the LMC itself.

Chemical abundances for the Sagittarius (Sgr) and Fornax dwarf galaxies from Sbordone et al. (2007; cyan points in Figure 2), Letarte et al. (2007; blue filled circles; 2006; blue open squares) and also a few stars from Shetrone et al. (2003; blue open symbols) are also unlike the stars in the MWG. Both also show lower calcium and higher barium than Galactic stars, though Sgr probes stars at higher metallicities than the LMC, while Fornax samples stars at slightly lower metallicities. Sgr and Fornax have had similar masses to the LMC, but the fact that their chemical abundance ratios differ from one another and those of the LMC suggests that other processes have been important, and that the mass of a dwarf galaxy alone does not fully determine its chemical evolution.

The Sculptor dwarf galaxy has a lower mass than the LMC, which is reflected in the lower metallicity of the majority of its stars as determined by Hill et al. (2008; green points in Figure 2), with a few stars from Shetrone et al. (2003) and Geisler et al. (2005) – green open symbols. While the calcium abundances are lower than in the Galaxy at intermediate metallicities, they are quite similar to those of the very metal-poor Galactic stars, overlapping the Galactic stars near [Fe/H] = –1.8. The barium abundances are not significantly different from Galactic stars. These imply some similarities in the early chemical evolution of the stars in the Sculptor dwarf galaxy to the MWG halo stars, however it also shows the power of having more than one element to examine. While there are similarities in the most metal-poor stars, variations in star formation histories, gas infall rates, or supernova feedback yields have affected the α-element abundances (calcium) at the time when the galaxy had reached intermediate metallicities. These results are similar to a sample of stars analysed by Koch et al. (2008; magenta points in Figure 2) in the low mass Carina dwarf galaxy.

Figure 2. Calcium and barium abundances for stars in the dwarf satellites of the Galaxy, including the LMC (red), Sgr (cyan), Fornax (blue), Sculptor (green) and Carina (magenta). Open and closed circles are for field stars, open squares are results from stars in globular clusters in the dwarf galaxies. Representative error bars are shown for some stars in Sculptor. Clearly each dwarf galaxy has had a different chemical evolution from the others and from the stellar populations in the Galaxy. This effect can be seen in the [Ca/Fe] plot by a variation in the metallicity when Type Ia supernovae start to contribute iron (the knee where the ratio slopes downwards), and in the [Ba/Fe] plot where the yields of s-process barium are higher from the AGB stars (the high values occurring at high metallicities).



Interpreting chemical signatures in dwarf galaxies

The most impressive result from the calcium/iron and barium/iron ratios in Figure 2 is simply that each dwarf galaxy has its own chemical evolution. This was expected since each has its own unique colour-magnitude diagram, indicating significantly different star formation histories (SFH). Precise interpretation of effects of the SFH versus other chemical evolution parameters is complicated (see further discussion below). At the very least, we can see that the dwarfs with higher luminosities (and presumably masses) that have had more ongoing star formation, as reflected in the distribution of stars in their colour-magnitude diagrams, do have more stars at higher metallicities (e.g., the LMC versus Sculptor). While metallicity does not have to scale with mass, it is reasonable to expect that galaxies with more baryons will be able to form more stars over time, and therefore build up their metallicities to higher levels than those with less gas.

The two abundance ratios examined in Figures 1 and 2 tell us that the build up of these elements has occurred differently in each galaxy as well, e.g., new contributions from lower mass stars happened at different *metallicities* in each galaxy (we cannot say at different ages, because there is no universal age-metallicity relationship). This can be seen in the different positions of the knee for each element and in each galaxy. The knees themselves are difficult to see precisely because they occur at metallicities that were not well sampled in all of the dwarf galaxies, other than Sculptor. Examining only the calcium/iron ratio shows that the *most metal-poor* stars in each galaxy have similar alpha/iron ratios to the metal-poor stars in the Galaxy, however, at intermediate and high metallicities then the alpha/iron ratios are lower by varying degrees. Thus, the contribution to iron from low mass stars occurs at a different *metallicity* in each galaxy; in Sculptor, it occurs near [Fe/H] = –1.8, in Fornax and the LMC it occurs before [Fe/H] = –1.5, but we do not have data on a sufficient number of stars below that metallicity to be more certain. However, looking at the slopes of the calcium/iron ratios suggests that the LMC knee could be at the same metallicity as that for Sculptor (in spite of their significantly different masses and SFHs), whereas that for Fornax is at a lower metallicity, [Fe/H] ~ –2.0. The Sgr remnant is not well sampled at low metallicities, but examination of the slope suggests that the knee occurs at higher metallicity than in Sculptor, [Fe/H] ~ –1.0. The current data for Carina has too large a scatter to say much about the metallicity at which low mass stars began to contribute iron; this could be due to differences in the abundance analysis compared to the other analyses which were done more homogeneously, or it could be astrophysical and reflect a true and very large scatter in the Carina abundances due to its complex SFH. More data on this galaxy would certainly be interesting. Looking at the knee in the barium/iron ratios is similarly interesting.

Each galaxy has similar barium/iron ratios at the low metallicities sampled, which suggests similar r-process yields with the exception of Fornax, which may have had a higher r-process contribution (or retention of r-process elements from Type II supernovae). However, the barium/iron ratios are certainly higher in Fornax, the LMC and the Sgr remnant at higher metallicities, [Fe/H] > –1.0, when the barium abundance is mainly due to s-process contributions from AGB stars. This pattern is not seen in the Galaxy, nor the Sculptor dwarf galaxy. AGB yields are metallicity dependent – at lower metallicities, there are fewer iron seeds for slow neutron capture, thus first s-process peak abundances (such as yttrium) are sacrificed for the second and third s-process peak abundances (such as barium and lead), e.g., Travaglio et al. (2004); thus the higher barium/iron abundances suggest that lower metallicity AGB stars contributed to these higher s-process yields and that iron is primarily from the lower mass stars. We also note that these three galaxies have had more vigorous star formation rates at recent times (< 5 Gyr), thus the combination of their SFHs and chemical evolution has affected their recent AGB yields.

Chemical evolution models for the Sculptor galaxy have been published by Fenner et al. (2006) and Lanfranchi et al. (2006) with similar results to one another. One of the most interesting results from the Fenner et al. analysis was the degeneracy in the alpha/iron ratios between SFH and supernova feedback (see their Figure 2); the same pattern in alpha/iron ratios is possible no matter how different the star formation histories (they examined a SFH that ends at the moment of reionisation compared with a SFH that continues to intermediate ages, see their Figure 1), so long as the supernova feedback is adjusted to the data. This brings into question the value of the alpha/iron ratio as an indicator of chemical evolution! Fortunately, the heavy elements are not degenerate in these two parameters; when the supernova feedback is adjusted to fit the alpha/iron data, then the barium/iron ratio predictions are not the same. This shows the power and necessity of having many different chemical elements available for chemical evolution modelling of real systems. While their model with the continuous SFH fits the data from Shetrone et al. (2003) better than their other models, the larger sample size that we now have from Hill et al. (2008) no longer fits that model. Lanfranchi et al. (2008) have examined the chemical evolution of the heavy element abundances in six dwarf galaxies, including Sculptor, Carina and the Sgr remnant, yet did not predict the increasing abundances at high metallicities seen in Figure 2. New chemical evolution modelling of the Sculptor and other dwarf galaxies are now necessary.

New modelling of dwarf galaxies is being carried out (e.g., Jablonka, this conference). Marcolini et al. (2008) have used a 3D hydrodynamical simulation to examine the chemical properties of the inner regions of dwarf galaxies. They find that the stars in the inner region are relatively iron-rich and alpha-poor (as observed), but the 3D aspects of the models show that this pattern differs from the outer regions and also that the kinematics of the outer regions are hotter (as observed by e.g., Battaglia et al., 2006). This model does not currently examine the heavy elements.

Chemical comparisons between the dwarf galaxies and the MWG

Only the metal-poor Galactic halo has any chemical signatures in common with the dwarf galaxies; at the lowest metallicities in these systems, the alpha/iron and heavy/iron abundances are in good agreement (with the possible exception of Fornax where the r-process barium/iron ratios may be higher; see Figure 2). If this is true, then it appears that the earliest stages of star formation yield similar results in all systems and/or that the metal-poor halo of the Galaxy built up from the accretion of small dwarf galaxies at the earliest epochs, before the dwarf galaxies had any significant chemical evolution of their own.

Another way to test this proposition is from the shape of the metallicity distribution function (MDF) of the most metal-poor stars. Helmi et al. (2006) compared the metal-poor tails of the MDFs of the Galaxy and four dwarf spheroidal galaxies, but found the dwarf galaxies all have similar and sharper declining tails (their Figure 3). The conclusion was that the metal-poor Galactic halo could not come from the accretion of dwarf spheroidal galaxies. There are three other possible interpretations. Schoerck et al. (2008) have rescaled the Galactic MDF for a minor observational bias and selection function of the Hamburg/ESO Survey sample and suggest that the new Galactic MDF has a sharper metal-poor tail, in good agreement with the dwarf spheroidal galaxies. The rescaled MDF is normalised and compared to the dwarf galaxies at [Fe/H] = −2.0, a value that may be too high since significant chemical evolution can occur in the dwarfs by the time this metallicity is reached. However normalising and comparing the MDF at [Fe/H] = −2.5, as was done by Helmi et al. (2006) has a less significant effect on the original MDF and thus improves the comparison with the dwarfs, but still does not eliminate the inconsistencies. The second option relies on the contribution of the newly discovered ultra-faint dwarf galaxies (e.g., Belokurov et al., 2007). The majority of the stars in these galaxies are more metal-poor than the majority of stars examined in the other dwarf galaxies (e.g., Simon & Geha, 2007; Kirby et al., 2008). Characterising these galaxies and examining their MDFs could provide a missing link in our current testing of the hierarchical accretion of small systems in the early stages of galaxy formation.
The third option for the difference in the MDF between the well-studied dwarf spheroidal galaxies and the MWG is the unknown characteristics of the old stellar populations in the isolated dwarf irregular galaxies. Although these galaxies are more luminous, contain gas and have current star formation, their old populations have been unexplored chemically because of their distance and thus the faintness of their red giant stars. The only detailed analyses from calcium triplet spectroscopy of red giants in a dwarf irregular galaxy include ~ 20 stars in NGC 6822 (Tolstoy et al., 2001) and ~ 80 stars in the Wolf-Lundmark-Melotte Galaxy (WLM; Leaman et al., 2008). The analysis of the stars in WLM included 13 old stars, which is a very small number, but enough to suggest that the old population may have spheroidal kinematics unlike the younger populations or the H I gas that is rotationally supported.

The calcium triplet data for the red giants in NGC 6822 did not include stars with old ages (from isochrones), however similar work on the carbon stars (AGB stars with intermediate ages) by Demers et al. (2006) has come to the same conclusion, that the young stars have disc-like kinematics, but not the AGB stars which have spheroidal kinematics. Even the H I disc is peculiar in NGC 6822; de Blok & Walter (2000) have shown there is a hole in the H I distribution on one side of the disc and an apparent overdensity on the other side (which they suggest could be the core of a recently merged dwarf). Could all of the dwarf irregular galaxies really be dwarf spheroidal galaxies that have had a recent merger with a gas-rich system (or even just an H I filament), where the gas is in the orbital plane of the merger? Simulations by Brook et al. (2007) do suggest that polar ring galaxies could be a natural and common occurrence in the evolution of the dwarf galaxies. It is exciting that this is a testable prediction through examination of the metallicities and kinematics of the Local Group dwarf irregular galaxies, and that these galaxies, since they formed and evolved in relative isolation, could be different to the dwarf spheroidals and provide new information on the nature of unperturbed dwarfs at early epochs.

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