

Galactic chemical evolution: the observational side

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In this review I first outline some interesting ideas in chemical evolution, necessary for understanding the evolution of galaxies from measured elemental abundance ratios. I then discuss abundance results from studies of stars in Local Group dwarf galaxies and the globular cluster Omega Cen. Finally, I present a qualitative scenario of prolonged chemical evolution in a leaky box that can explain the observed abundance ratios trends in these dwarf systems.

Unfortunately, space limitations prevent a comprehensive discussion of the vast field of observational chemical evolution, so I have limited this paper to a few interesting subtopics. I have completely omitted the Galactic bulge; this may be as well, because there is some disagreement over the measured abundance ratios, except for [O/Fe] which follows the thick disk trend.

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1. An Introduction to Chemical Evolution

This paper is mostly concerned with the observational side of chemical evolution; however, in order to interpret the measured abundance ratios it is necessary to understand some basic qualitative concepts in chemical evolution theory.

In the 1950s both observations and theory (Chamberlain & Aller 1951; Hoyle 1955; Burbidge et al. 1957; Preston 1959) indicated that most of the chemical elements were produced by stars and that the Galaxy had undergone chemical evolution due to nuclear processing by many generations of stars.

1.1 The Simple Model

Perhaps the most basic chemical evolution model is the Simple Model of van den Bergh (1962) and Schmidt (1963.) This idealized scenario begins with a mass of metal-free gas, and a constant rate of star formation (SFR), in stellar generations, with a fixed distribution of stellar masses, or initial mass function (IMF). Each stellar generation produces an identical mass of metals from its massive stars, and fossil remnants from the dwarfs; the metals are instantaneously, and homogeneously, mixed into the unused gas, thus increasing the gas metal abundance. There is no inflow or outflow of material to the region, i.e., it is a “closed box”. Searle & Sargent (1972) introduced the concept of “*yield*”, which is the ratio of the mass of metals produced to the mass locked-up in low mass stars. In a Simple Model that runs to gas exhaustion, the average metallicity of the dwarfs is equal to the “*yield*”. Thus, the average of the metallicity distribution function (MDF) for a stellar system indicates the yield of metals from its stars.

The Simple Model age-metallicity relation is linear, while the MDF is logarithmic: for example, there are a thousand stars at $[\text{Fe}/\text{H}]=0$ for each star at $[\text{Fe}/\text{H}]=-3$. The observed solar neighborhood MDF shows a deficiency in metal-poor stars compared to the Simple Model; this deficit is known as the “*G-dwarf problem*”. The widely accepted explanation for the G-dwarf problem is that inflow of low-metallicity gas has occurred during the evolution of the Galactic disk, with an exponential decay timescale of ~ 5 Gyr (e.g., Sommer-Larsen 1991). At early times there was relatively little gas present so only small numbers of metal-poor G-dwarf stars were produced, compared to later epochs when the metallicity was higher.

Chemical evolution models with increasing complexity have been constructed, and they are now much more realistic; for discussion of these I refer the reader to the talk by Nick Prantzos at this conference. However, I find the Simple Model a useful heuristic tool and a good starting point for thinking about ideas in chemical evolution.

1.2 The Metallicity Distribution Function

While the mean metallicity of a Simple Model can be used to determine the yield, in stellar systems the mean of the MDF can be affected in several ways:

The mean $[\text{Fe}/\text{H}]$ for the Galactic halo, found by Hartwick (1976), is near -1.6 dex, which he explained as due to the halo losing its gas before chemical evolution could go to completion; thus, *gas outflow* terminated halo evolution at low metallicity.

This contrasts with the explanation for the metallicities of gas and young stars in the LMC and SMC, at $[\text{Fe}/\text{H}]=-0.3$ and -0.6 dex, respectively (e.g., Russell & Dopita 1990). The presence of

young and old stars (supergiants, RGB and carbon stars) and high gas fractions suggest prolonged evolution, and a low SFR, for these dwarf galaxies; thus, the metallicity may not have had time to reach solar values. However, outflows could also explain the low $[\text{Fe}/\text{H}]$ of the LMC and SMC; realistic models are required for a full understanding.

Changes in the IMF can also affect the mean metallicity: the yield depends on the mass of iron produced by massive stars, and the mass locked-up in low-mass dwarf stars, both of which varies with the IMF. In this way Ballero et al. (2007) employed an IMF weighted to massive stars to explain how rapid bulge formation, with no Fe from SNIa, could produce a high mean metallicity, near the solar value. An alternative, suggested by A. Pipino, is that the bulge experienced huge mass inflows early-on, giving an extreme G-dwarf problem and higher mean $[\text{Fe}/\text{H}]$.

2. Alpha Elements

Wallerstein (1962) and Conti (1967) first recognized the factor of two enhancements of Mg, Si, Ca, Ti and O in Galactic halo RGB stars. These even-numbered elements, from O to Ti, are referred to as α -elements, although no single nuclear reaction is responsible for their synthesis. Plots of $[\alpha/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ in the solar neighborhood show a plateau below $[\text{Fe}/\text{H}] \sim -1$, followed by a steady decline to $[\alpha/\text{Fe}] \sim 0$ at $[\text{Fe}/\text{H}] \sim 0$. The trend is, actually, a composite of the ratios transitioning from halo, to thick disk and thin disk populations.

Tinsley (1979) proposed that the trend of $[\text{O}/\text{Fe}]$ with $[\text{Fe}/\text{H}]$ resulted from the time delay between SNII and SNIa. At early times, and low $[\text{Fe}/\text{H}]$, the SNII $[\text{O}/\text{Fe}]$ values prevailed; subsequent addition of SNIa lowered the $[\text{O}/\text{Fe}]$ ratio because SNIa produce Fe but no O. A Simple Model linear age-metallicity relation and the observed $[\text{O}/\text{Fe}]$ decline, beginning near $[\text{Fe}/\text{H}] \sim -1$, indicates a ~ 1 Gyr delay for the onset of significant SNIa Fe production, roughly consistent with detailed calculations of Matteucci & Greggio (1986). I note that while the most massive SNIa progenitors have delays ~ 0.1 Gyr, a significant effect on $[\text{O}/\text{Fe}]$ does not occur until much later.

The calculations of Matteucci & Brocato (1990, henceforth MB90), adapted in Figure 1, showed that the down-turn, or knee, in the $[\text{O}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ plot should depend on the SFR. High SFR systems, like bulges and giant ellipticals, reach high $[\text{Fe}/\text{H}]$ before the SNIa time-delay, and the decline in $[\text{O}/\text{Fe}]$; similarly, low SFR systems, such as dwarf galaxies, should show a decline in $[\text{O}/\text{Fe}]$ at low $[\text{Fe}/\text{H}]$.

MB90's strict age-metallicity relation (probably unrealistic), meant that only the most massive stars contributed to the composition at the lowest metallicity. This is the cause for MB90's gentle slope to higher $[\text{O}/\text{Fe}]$ below the knee, because the O/Fe yield ratio increases with increasing SNII mass. Massive SNII produce higher $[\text{O}/\text{Fe}]$ due to their larger envelopes, where O is produced, and because of greater fallback of Fe, than lower mass SNII. Following this idea Wyse & Gilmore (1993) showed that shallower IMF slopes (i.e., weighted to massive stars) produce larger $[\text{O}/\text{Fe}]$ ratios. Thus, the $[\text{O}/\text{Fe}]$ ratios below the knee can constrain the IMF slope, while the $[\text{Fe}/\text{H}]$ of the knee can constrain the SFR (and formation timescale) for a stellar system (see Figure 1).

The alpha elements can be divided into two categories: *hydrostatic* (O and Mg), made in the envelopes of massive SNII progenitors before the explosive event, and *explosive* (Si, S, Ca, and Ti), principally made during the explosion. Supernova nucleosynthesis calculations (e.g., Woosley & Weaver 1995) show that O and Mg are made by progenitors with masses $\sim 35M_{\odot}$, while the

production of Si through Ca peaks near 20–25 M_{\odot} SNII progenitors. Thus, the ratio of [Mg/Ca] should be sensitive to the IMF slope.

The O yield from massive stars is also predicted to be sensitive to metallicity (e.g., Maeder 1992), due to the stripping of the envelope by stellar winds, related to the Wolf-Rayet phenomena. In this way the [C/O] yield ratio increases with [Fe/H], since carbon that would normally be burned to oxygen is removed from the star. This mechanism appears to have operated in the Galactic thick disk and bulge (Cescutti et al. 2009). Wolf-Rayet stars produced via envelope stripping from binary mass transfer should also decrease the oxygen yield and increase the [C/O] ratio.

Thin disk and Galactic bulge [O/Mg] trends show a steep decline above [Fe/H] ~-1 (see McWilliam et al. 2008). While the bulge results are now not agreed upon by all observers, there is no disagreement for the thin disk trend. The [O/Mg] decline in the disk can result from a decrease in oxygen yields from massive stars due to envelope stripping by metallicity-dependent stellar winds (e.g., Cescutti et al. 2009).

While predicted SNIa yields make effectively no O or Mg, they do make significant amounts of Ca (e.g., Nomoto 1984), near the solar [Ca/Fe] ratio. Thus, Tinsley’s scenario suggests a smaller amplitude change in [Ca/Fe] than [O/Fe].

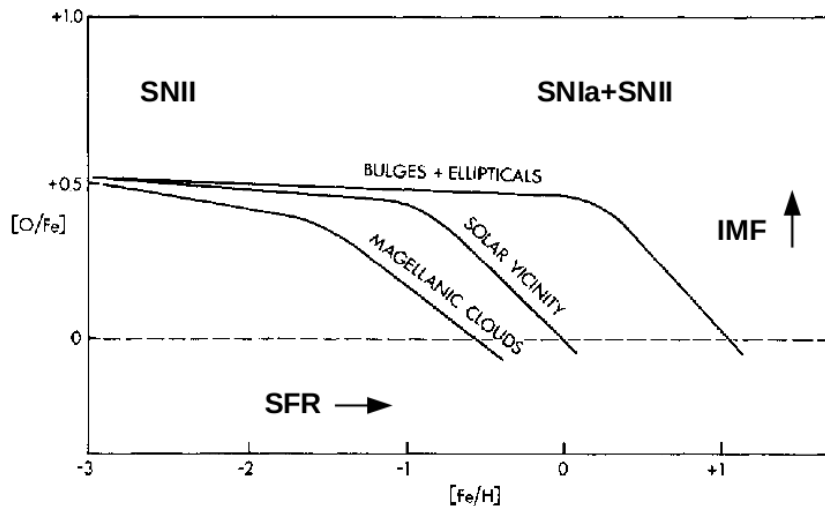


Figure 1: Predicted [O/Fe] versus [Fe/H] for systems with different SFR, modified from Matteucci & Brocato (1990).

3. The Chemical Composition of Dwarf Galaxies

3.1 The Magellanic Clouds

Early abundance studies of Magellanic Cloud stars were restricted to bright supergiants (e.g., Spite et al. 1986; Russell & Bessell 1989; McWilliam & Williams 1989), which only traced the very recent composition; typically, the supergiants were hot, with subsequent uncertainty about non-LTE effects on the results.

Later abundance studies of LMC red giant branch (RGB) stars probed all ages; however, initial results from Hill et al. (1995) and Korn et al. (2002) were too few to discern a trend of $[\text{O}/\text{Fe}]$ with $[\text{Fe}/\text{H}]$. Smith et al. (2002), with 12 LMC RGB stars, plus the earlier results, showed a steep decline in $[\text{O}/\text{Fe}]$ well below that for the Milky Way, with $[\text{O}/\text{Fe}]$ lower by almost 0.3 dex at the metal-rich end (near $[\text{Fe}/\text{H}]=-0.2$ dex). It was not clear whether the $[\text{O}/\text{Fe}]$ ratios at the low $[\text{Fe}/\text{H}]$ end are the same in the LMC and Galaxy; this zero-point issue should be resolved.

A large sample of LMC RGB stars studied by Pompéia et al. (2008) provided $[\alpha/\text{Fe}]$ trends for O, Mg, Ca, Si and Ti. The handful of O/Fe abundance ratios overlapped with Smith et al. (2002). Relative to the Galaxy the LMC $[\text{Ca}/\text{Fe}]$ and $[\text{Ti}/\text{Fe}]$ ratios of Pompéia et al. (2008) are deficient at all $[\text{Fe}/\text{H}]$; remarkably, $[\text{Si}/\text{Fe}]\sim 0$ for all $[\text{Fe}/\text{H}]$. The average $[\text{Mg}/\text{Fe}]$ LMC trend is deficient, relative to the Milky Way, below $[\text{Fe}/\text{H}]=-0.6$, but could be described as bimodal, as if halo and thin disk populations overlapped in $[\text{Fe}/\text{H}]$. Thus, there is rough confirmation that $[\text{O}/\text{Fe}]$ and the other $[\alpha/\text{Fe}]$ ratios are deficient in the LMC, relative to the solar neighborhood, as predicted by MB90, but further investigation is warranted.

3.2 Alpha Elements in Local Group Dwarf Galaxies

The first Local Group dwarf galaxy abundance measurements, for Draco, Ursa Minor and Sextans, by Shetrone et al. (2001), gave an average of Mg/Fe, Ca/Fe and Ti/Fe ~ 0.2 dex deficient, relative to the Milky Way (O was not measured), qualitatively consistent with the predictions of MB90.

Shetrone's results provoked an important question: if the halo is composed of accreted dwarf galaxy fragments, then why does it possess higher $[\alpha/\text{Fe}]$ than the Local Group dwarf galaxies? The answer is that the halo must be made mostly of early dwarf galaxy fragments, which had not yet suffered significant enrichment by SNIa when they were accreted. Notwithstanding, there are plenty of examples of Galactic halo stars with low $[\alpha/\text{Fe}]$ (e.g. Nissen & Schuster 1997; Brown et al. 1997).

For the more metal-rich stars in the Sagittarius dwarf spheroidal galaxy (henceforth Sgr dSph) $[\alpha/\text{Fe}]$ deficiencies were found by Smecker-Hane & McWilliam (2002), McWilliam & Smecker-Hane (2005a), Sbordone et al. (2007), and Carretta et al. (2010). However, the metal-poor Sgr dSph stars possessed normal halo α -element enhancements. Similar results for the $[\text{O}/\text{Fe}]$ ratios in the Sculptor dSph were found by Geisler et al. (2005); and Letarte et al. (2010) recently found low $[\alpha/\text{Fe}]$, for Mg, Si, Ca and Ti, in the Fornax dSph, although no O measurement was made. Cohen & Huang (2009,2010) found low metallicity knees in the $[\alpha/\text{Fe}]$ trends for the Draco and Ursa Minor dSphs, and claimed halo-like ratios for the most metal-poor members of these dwarf galaxies.

These abundance results are qualitatively consistent with Tinsley's time-delay scenario and the predictions of MB90. They are also consistent with the idea that the halo was formed from accreted dwarfs at very early times, before the bulk of SNIa had occurred. Subsequent enrichment of present day dwarf galaxies decreased the $[\alpha/\text{Fe}]$ ratios, but the older, metal-poor, stars in the nearby dSphs have halo-like compositions.

3.3 Sodium and Aluminium

Bonifacio et al. (2000), Smecker-Hane & McWilliam (2002), and Sbordone et al. (2007)

found $[Al/Fe]$ and $[Na/Fe]$ deficiencies of ~ 0.3 – 0.4 dex in the Sgr dSph; results of Carretta et al. (2010) are inconclusive.

For the LMC RGB stars Smith et al. (2002) found a mean $[Na/Fe] = -0.3$ dex, similar to the results from F–G supergiants by Hill et al. (1995). Pompéia et al. (2008) found Na/Fe deficiencies of ~ 0.3 – 0.4 dex for her large sample of LMC RGB stars, relative to the solar neighborhood. For the Draco and UMi dSphs Cohen & Huang (2009, 2010) found Na/Fe deficiencies, relative to the Galaxy, for the metal-rich end of their sample, similar to their α -element deficiencies. Large $[Na/Fe]$ deficiencies, ~ -0.7 dex were found for the stars in the Fornax dSph, by Letarte et al. (2010), for which the mean $[Fe/H]$ was -0.8 dex. For the Sculptor dSph Geisler et al. (2005) found mean $[Na/Fe]$ and $[Al/Fe]$ near -0.5 and -0.4 dex, respectively, similar to the deficiencies found in the Sgr dSph. Thus, it appears that the Na deficiencies, at least, are common-place among the dwarf galaxies, and that when measured Al is also deficient. More work on Al/Fe ratios would be useful.

The main source for Al and Na is thought to be the hydrostatic phase of SNIi progenitors (e.g., Woosley & Weaver 1995), modulated by the neutron excess (i.e., metallicity) as described by Arnett (1971). Thus, Al and Na should behave much like alpha-elements, but with a metallicity-dependent yield trend imposed; so, it is not surprising that Al and Na are deficient in dwarf galaxies, where alpha-element deficiencies are also observed.

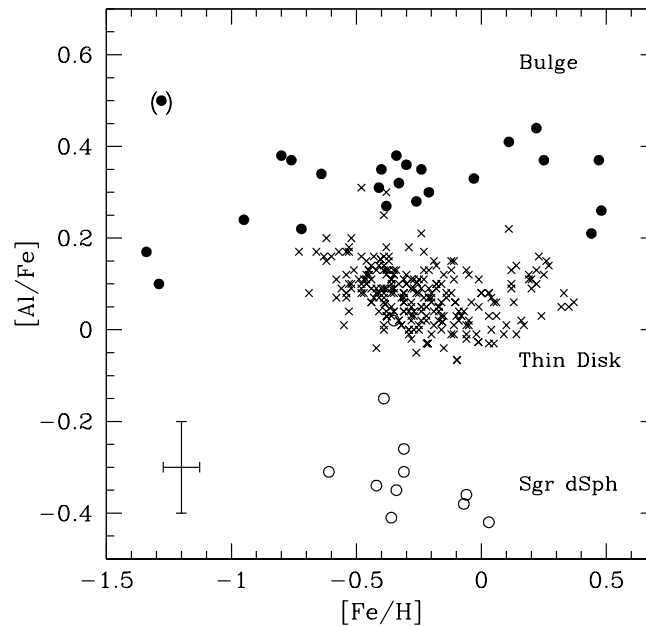


Figure 2: $[Al/Fe]$ for the Sgr dSph, Galactic thin disk, and the Galactic bulge, adapted from Fulbright et al. (2007).

In Figure 2 I show $[Al/Fe]$ versus $[Fe/H]$ for three systems: Sgr dSph, the thin disk, and the Galactic bulge, from Fulbright et al. (2007). The ~ 0.8 dex difference between the bulge and Sgr dSph $[Al/Fe]$ ratios, at the same $[Fe/H]$ values, is remarkable. In the Tinsley (1979) time-delay scenario, if the bulge $[Al/Fe]$ reflects the pure SNIi ratio, then the Fe in the Sgr dSph is $\sim 85\%$ SNIa

material; however, if the bulge contains any Fe from SNIa, then the Sgr dSph SNIa Fe fraction must be even greater. Thus, the Sgr dSph iron-peak elements seem to be dominated by SNIa material, and this system would be useful to compare with predicted SNIa iron-peak yields. In Figure 2 the RGB stars of the Sgr dSph and the bulge have similar $[\text{Fe}/\text{H}]$, and temperature, so non-LTE effects are unlikely to explain the Al and Na abundance differences.

3.4 S-Process Enhancements

Mild enhancements in heavy s-process elements in the LMC supergiants, were first noted by Russell & Bessell (1989), McWilliam & Williams (1991) and Hill et al. (1995). For the dwarf galaxies the small numbers of stars studied by Shetrone et al. (2001) showed large dispersion, with possible slight enhancements in the mean heavy s-process noted. However, firm detection of s-process enhancements in nearby dwarf galaxies were first seen in Sgr dSph RGB stars, by Smecker-Hane & McWilliam (2002), showing a steady increase in $[\text{La}/\text{Fe}]$ with increasing $[\text{Fe}/\text{H}]$, up to $[\text{La}/\text{Fe}] = +1$ dex at $[\text{Fe}/\text{H}] \sim 0$. Remarkably, the Ba II lines were too saturated in the Sgr dSph for reliable abundance measurement. Figure 3 shows plot of $[\text{La}/\text{Eu}]$ versus $[\text{La}/\text{H}]$ adapted from McWilliam & Smecker-Hane (2005a), indicating the dominance of the s-process, with a locus that indicates halo composition plus at least 95% s-process above $[\text{Fe}/\text{H}] \sim -0.7$ dex. Notably, the $[\text{Eu}/\text{Fe}]$ ratio enhancement, at roughly $+0.3$ dex, is due to the s-process, despite the fact the solar Eu is $\sim 95\%$ r-process. An r-process assignment can only be identified from the neutron-capture element abundance ratios, not the ratio to iron.

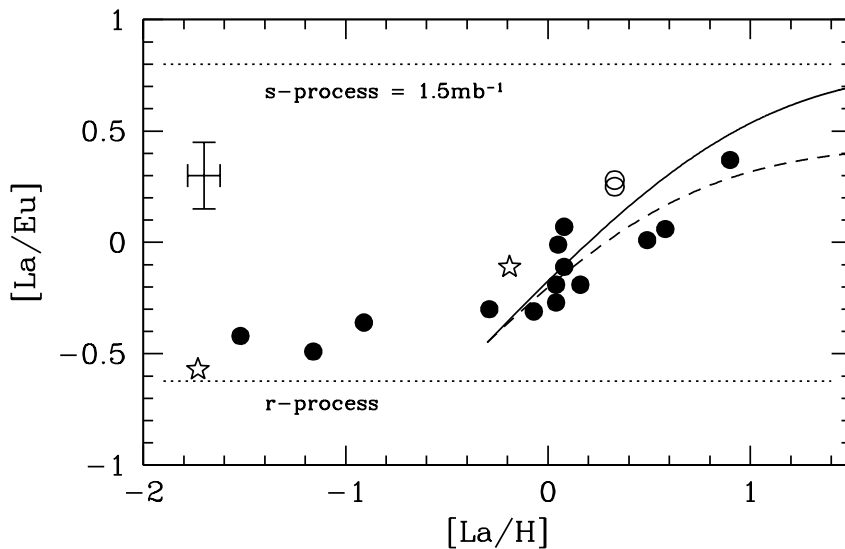


Figure 3: $[\text{La}/\text{Eu}]$ versus $[\text{La}/\text{H}]$ for the Sgr dSph, adapted from McWilliam & Smecker-Hane (2005a). Solid line shows locus of pure s-process added to an original composition; dashed line indicates the locus of 95% s-process plus 5% r-process added to the original composition.

The same authors found normal Y abundances (a light s-process element), giving a high $[\text{La}/\text{Y}]$, which measures the heavy/light, or $[\text{hs}/\text{ls}]$, ratio; the enhanced $[\text{hs}/\text{ls}] \sim 0.5$ dex, occurs

for Sgr dSph stars for $[\text{Fe}/\text{H}]$ between -0.7 dex and the solar value.

Busso et al. (1999) showed that high $[\text{hs}/\text{ls}]$ ratios occur in metal-poor AGB s-processing. At low metallicity the ratio of iron seed nuclei to neutrons is low, so each seed nucleus captures many neutrons, thus pushing the synthesis to heavy nuclei. From the $[\text{La}/\text{Y}]$ ratio McWilliam & Smecker-Hane (2005a) concluded that the AGB s-processing took place in Sgr dSph stars with $[\text{Fe}/\text{H}]$ near -0.6 or below -1 , which was much lower $[\text{Fe}/\text{H}]$ than the solar metallicity Sgr dSph RGB stars studied. Thus, the Sgr dSph must have been polluted with ejecta from metal-poor AGB stars.

Similar s-process enhancements and patterns have been found in the LMC RGB stars by Pompéia et al. (2008), in the Fornax dSph by Letarte et al. (2010), and in the Ursa Minor dSph by Cohen & Huang (2010); thus, this appears to be a general feature seen in the most metal-rich stars of dwarf galaxies.

S-process enhancements have long been known for the Galactic globular cluster, Omega Cen (e.g., Vanture, Wallerstein & Brown 1994; Smith et al. 2000). I note that a plot of $[\text{La}/\text{Eu}]$ versus $[\text{La}/\text{H}]$ from the data of Johnson & Pilachowski. (2010) shows, for nearly all stars, a locus that is consistent with the addition of pure s-process material to the composition of the oldest stars in Omega Cen, similar to Sgr dSph (Figure 3 here) from McWilliam & Smecker-Hane (2005a).

Together with similar Cu and Mn abundances, this chemical similarity with the Sgr dSph suggests a common history, and that Omega Cen may be the core of an accreted dwarf galaxy. The main chemical difference is that Omega Cen possesses halo-like, enhanced, $[\alpha/\text{Fe}]$ ratios. I find this difference both puzzling and fascinating, because it is apparently inconsistent with the Tinsley time-delay scenario; thus, the α -enhancements in Omega Cen may provide a critical clue for understanding chemical evolution.

The s-process abundance patterns in these dwarf systems indicates significant nucleosynthesis by metal-poor AGB stars, which McWilliam & Smecker-Hane (2005a) suggested resulted from leaky box chemical evolution, in which the MDF possessed a larger fraction of metal-poor stars than the solar neighborhood. Initially, these galaxies would have formed early, metal-poor, populations proportional to the mass of gas, but by late times a large fraction of the gas had leaked-out, such that the ejecta from the now relatively large population of old, metal-poor, AGB stars dominated neutron-capture element abundance pattern of the late-time gas. Presumably, leaky-box chemical evolution must be quite general and apply to many dwarf galaxies, and it seems reasonable that the amplitude of the effect may be greater for lower-mass galaxies.

3.5 Manganese and Copper

The solar neighborhood (i.e., halo, thin and thick disk populations) trend for $[\text{Cu}/\text{Fe}]$ shows a sub-solar plateau, near $[\text{Cu}/\text{Fe}]=-0.6$ dex, below $[\text{Fe}/\text{H}]\sim-1.5$; above that the $[\text{Cu}/\text{Fe}]$ ratio increases approximately linearly with $[\text{Fe}/\text{H}]$, toward the solar composition at $[\text{Fe}/\text{H}]=-0.5$, and remains constant thereafter (see Mishenina et al. 2002; Simmerer et al. 2003). It appears that the thin disk $[\text{Cu}/\text{Fe}]$ ratio is constant, while there is an approximately linear $[\text{Cu}/\text{Fe}]$ trend with $[\text{Fe}/\text{H}]$ for the transition from halo to thick disk populations.

McWilliam & Smecker-Hane (2005b) found severe $[\text{Cu}/\text{Fe}]$ deficiencies, up to nearly 0.6 dex, in the Sgr dSph for $[\text{Fe}/\text{H}]$ above -0.8 dex. In the same month Geisler et al. (2005) found similar $[\text{Cu}/\text{Fe}]$ deficiencies in the Sculptor dwarf galaxy, but at lower $[\text{Fe}/\text{H}]$ than in the Sgr dSph. These

deficiencies were reminiscent of those found in Omega Cen by Cunha et al. (2002). More recently, Pompeia et al. (2008), Figure 3 here, found large $[\text{Cu}/\text{Fe}]$ deficiencies in LMC stars with $[\text{Fe}/\text{H}]$ above -1 , almost as if the low $[\text{Cu}/\text{Fe}]$ ratios in the halo has been extended up to the highest $[\text{Fe}/\text{H}]$ in the LMC. Carretta et al. (2010) have confirmed the low $[\text{Cu}/\text{Fe}]$ ratios in the Sgr dSph. Included without discussion in their paper, the $[\text{Cu}/\text{Fe}]$ ratios of Cohen & Huang (2010) for the UMi dSph are deficient by ~ 0.4 dex, relative to the Milky Way. Clearly, Cu deficiencies are a common, perhaps ubiquitous, signature of dwarf galaxies.

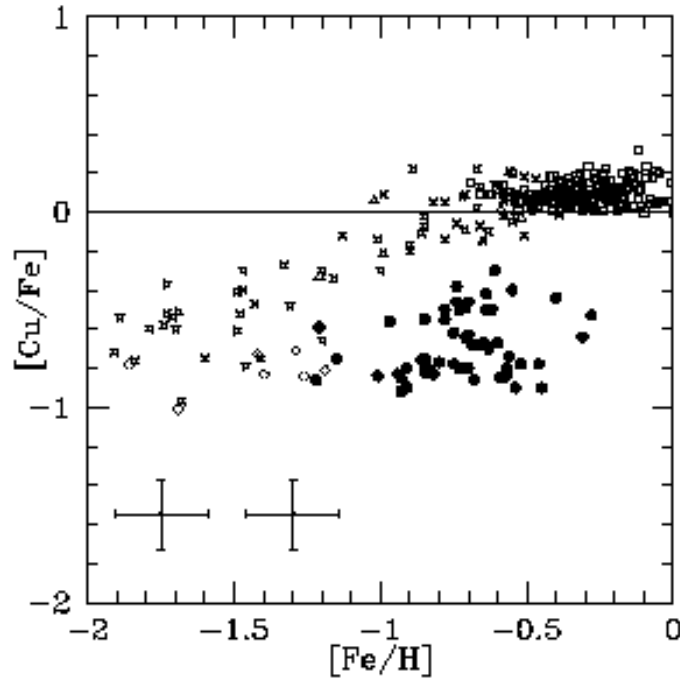


Figure 4: $[\text{Cu}/\text{Fe}]$ for the LMC (filled circles) taken from Pompéia et al. (2008); similar trends are also seen in Sgr, Sculptor, and UMi dSphs. Other symbols represent Milky Way stars.

Bisterzo et al. (2004) concluded that the *weak sr-process* in massive stars is the principle source of Cu in the Galaxy, occurring during convective shell C burning of SNI progenitors, and that SNIa and AGB stars do not produce significant quantities of Cu. The metallicity-dependence of the weak sr-process explains the positive slope of $[\text{Cu}/\text{Fe}]$ with $[\text{Fe}/\text{H}]$, while the production of iron from SNIa explains the flattening-out of the slope in the thin disk.

The Cu deficiencies in dwarf galaxies indicates a paucity of high-mass stars in these systems, although the metallicity-dependence could play a role. This lack of material from massive stars is consistent with the prolonged star formation and leaky box scenario suggested by the abundances of the α and s-process elements. By this same argument, one would expect that bulges and giant ellipticals, or systems with high SFR and/or an excess of high-mass stars, should possess $[\text{Cu}/\text{Fe}]$ enhancements, relative to the solar neighborhood.

In the solar neighborhood $[\text{Mn}/\text{Fe}]$ shows approximately constant deficiency, near -0.4 dex, below $[\text{Fe}/\text{H}]=-1$, but increases roughly linearly with increasing $[\text{Fe}/\text{H}]$ to $[\text{Mn}/\text{Fe}]=0.0$ at solar metallicity (Sobeck et al. 2006; Gratton 1989). Because this trend looks like the mirror image

of the $[\alpha/\text{Fe}]$ trend with $[\text{Fe}/\text{H}]$, Gratton (1989) suggested that Mn is over-produced in SNIa. In this scenario the time-delay for the onset of SNIa would be responsible for the increase in $[\text{Mn}/\text{Fe}]$ above $[\text{Fe}/\text{H}] \sim -1$. If Gratton's suggestion is correct, the time delay scenario of Tinsley (1979) and MB90 would predict that $[\text{Mn}/\text{Fe}]$ is enhanced in low SFR dwarf galaxies, but deficient in high SFR systems, such as bulges and elliptical galaxies.

Measurements of $[\text{Mn}/\text{Fe}]$ abundance ratios in Sgr dSph RGB stars by McWilliam et al. (2003) showed a deficiency relative to the solar neighborhood trend by ~ 0.2 dex, in stark contrast to the expectations if Mn is over-produced by SNIa. Similar Mn deficiencies have been seen in Omega Cen by Cunha et al. (2010), but Carretta et al. (2010) did not confirm this finding in their sample of Sgr dSph stars. The low $[\text{Mn}/\text{Fe}]$ ratios for LMC supergiants, by Hill et al. (1995), are similar to the deficiencies seen in the Sgr dSph; more work on LMC $[\text{Mn}/\text{Fe}]$ ratios is warranted.

McWilliam et al. (2003) also found that the $[\text{Mn}/\text{Fe}]$ trend with $[\text{Fe}/\text{H}]$ in the Galactic bulge is similar to the solar neighborhood; assuming that the bulge formed on a short timescale, this is also inconsistent with the expectations if SNIa over-produce Mn, since a Mn deficiency would be predicted for the bulge. Arnett (1971) concluded that the Mn yield is metallicity-dependent in SNII; McWilliam et al. (2003) speculated that this metal-dependence should also apply to SNIa, which also synthesize the iron-peak elements. Thus, low $[\text{Mn}/\text{Fe}]$ ratios in Sgr dSph could be explained by metal-poor SNIa, which might be expected to accompany the metal-poor AGB population.

4. A Qualitative Model for Dwarf Galaxy Evolution

The chemical properties of the dwarf galaxies, outlined above, can be qualitatively explained in a model of prolonged chemical enrichment with on-going gas-loss, or leaky-box chemical evolution.

The low $[\alpha/\text{Fe}]$ trends, the Na and Al deficiencies, and the low $[\text{Cu}/\text{Fe}]$ ratios at higher metallicities, all indicate low SNII/SNIa ratios in dwarf systems, consistent with low SFRs and prolonged evolution. In particular, the comparison of $[\text{Al}/\text{Fe}]$ from Sgr dSph to thin disk to bulge suggests that the Sgr dSph iron-peak material near solar $[\text{Fe}/\text{H}]$ is $\sim 85\%$ SNIa. Thus, the dwarf galaxies are good places to look for the signature of SNIa nucleosynthesis.

These prolonged formation timescales are supported by the significant enhancements of s-process material, produced by relatively low mass AGB stars with long main sequence lifetimes. In the case of the Sgr dSph the ages and metallicities of its associated globular clusters also indicate a long formation timescale.

The low mean metallicities and high $[\text{hs}/\text{ls}]$ s-process ratios provide strong evidence for significant mass-loss from the dwarf galaxies during their evolution. Without such a leaky box chemical evolution the high $[\text{hs}/\text{ls}]$ ratios from the metal-poor AGB stars would have been overwhelmed by low $[\text{hs}/\text{ls}]$ ratios at higher $[\text{Fe}/\text{H}]$, and the mean metallicities would be higher.

In a leaky box at early times a significant metal-poor population is formed, but much of the gas is lost from the galaxy during subsequent evolution, until at late times there is very little gas to form new generations of stars. Thus, there are very few SNII at late times to produce higher α/Fe , Al/Fe, Na/Fe, Cu/Fe ratios, and few high metallicity AGB stars producing low $[\text{hs}/\text{ls}]$ s-process ratios. However, by late times the old, metal-poor, population AGB stars eject significant

amounts of gas and s-process elements, and thus these dominate the abundance pattern of the neutron-capture elements of the younger, more metal-rich, population.

In this scenario an important question is: where do the iron-peak elements come from at late times? The answer is that they likely come from low-mass SNIa systems, which have prolonged main-sequence lifetimes, and are relatively metal-poor, and should accompany the old, metal-poor, AGB population. The low metallicity of the SNIa explains the measured low [Mn/Fe] ratios in the more metal-rich stars of the Sgr dSph and Omega Cen, since Mn yields are expected to be metallicity-dependent.

Detailed chemical evolution models are required to constrain the amount of gas lost from these dwarf galaxies. Other phenomena to be modelled include the retention of ejecta from various sources, such as AGB stars, SNIa, and SNII, which have very different kinetic energies; also, the effects of dark matter and cooling (i.e., metallicity) on gas retention. The models would be very helpful for understanding the evolution of these galaxies and to constrain the sites of nucleosynthesis for various elements, and constraining stellar yields. It would be helpful to have a set of predicted abundance ratios for dwarf galaxies from such detailed models, as a function of some mass-loss parameter. So far, most of the abundance anomalies found in dwarf galaxies were observed, not predicted.

Of significant interest is the role of the IMF in dwarf galaxy chemical evolution. In particular, a major question for understanding star formation in galaxies is whether the IMF slope is everywhere the same, but with reduced high-mass end cutoffs in dwarf systems. It is possible to probe the IMF with various element ratios that are sensitive to stellar mass (e.g., [Mg/Ca], [C/O]), although the interpretation may require modelling. Comprehensive CNO abundance results for dwarf galaxies, and other element ratios, such as [Rb/Zr] and D/H in these systems would provide interesting tests of the paradigm outlined here.

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