Metal-poor Galaxies in the Local Universe

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Abstract. A galaxy’s mean metallicity is usually closely correlated with its luminosity and mass. Consequently the most metal-poor galaxies in the local universe are dwarf galaxies. Blue compact dwarfs and tidal dwarfs tend to deviate from the metallicity-luminosity relation by being too metal-poor or too metal-rich for their luminosity, respectively. A less pronounced offset separates dwarf spheroidal (dSph) and dwarf irregular galaxies, making the former too metal-rich for their luminosity, which indicates different formation conditions for these two types of dwarfs. While environment (photo-evaporation through local re-ionization by massive galaxies, tidal and ram pressure stripping) govern the observed morphology-distance relation, intrinsic properties (in particular total mass) play a decisive role in dwarf galaxy evolution with respect to the time and duration of star formation and the amount of enrichment. The metallicity distribution functions of nearby dwarfs can be understood taking pre-enrichment, gas infall, and winds into account. Many dwarfs show evidence for inhomogeneous, localized enrichment. Ultra-faint dSphs, which may have formed their metal-poor stars at high redshift via H$_2$ cooling, show an overabundance of metal-deficient stars as compared to the (inner) Galactic halo, but may, along with classical dSphs, have contributed significantly to the build-up of the outer halo. The abundance ratios measured in the irregular Large Magellanic Cloud are consistent with the postulated early accretion of irregulars to form the inner Galactic halo.

Keywords: Galactic halo, Dwarf galaxies (elliptical, irregular, and spheroidal), Magellanic Clouds and other irregular galaxies, Origin, formation, evolution, age, and star formation, Chemical composition and chemical evolution, Stellar content and populations; radii; morphology and overall structure

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1. INTRODUCTION

Most galaxies in the local universe follow a metallicity-luminosity (or metallicity-mass) relation in the sense that more luminous galaxies also tend to be more metal-rich. Galaxies in the high-metallicity, high-mass regime with current stellar masses greater than $10^{10} M_\odot$ show very little increase in metallicity towards higher masses though [124], while there is a pronounced decline in metallicity towards lower luminosities (or stellar masses) and an increased scatter in the relation [124].

Taking three parameters into account, namely the stellar mass, the gas-phase metallicity, and the star formation rate, galaxies up to a redshift of $z \sim 2.5$ follow a fairly tight “fundamental metallicity relation” in this three-dimensional space [105]. At higher redshifts, galaxies show lower metallicities leading to increasing deviations from the relation. Here dilution by infall of pristine gas becomes a dominant factor despite active star formation as long as the dynamical time scales remain shorter than the chemical enrichment time scales [105]. At lower redshift outflows of enriched material become more important and a balance between infall and outflows develops [105], whereas interacting and merging galaxies deviate from the stellar mass-metallicity trend [111].
In this review, we consider metal-poor galaxies in the local Universe, i.e., galaxies at the low-luminosity, low-mass end of the metallicity-luminosity relation — thus, dwarf galaxies. Exactly where to draw the line between “dwarf” and “giant” galaxies is more a matter of definition than of physical difference. Often a simple luminosity criterion is used (e.g., a luminosity \( \leq 0.1 L_\star \) or \( M_V \leq -18 \) mag; see, e.g., [49]), which also excludes the massive galaxies along the classical Hubble sequence.

Dwarf galaxies cover a variety of morphological types, luminosities, present-day star formation activity, gas content, as well as environments [50]. Late-type, gas-rich, star-forming dwarfs (such as dwarf spirals, dwarf irregulars, or blue compact dwarfs) are usually found in low-density environments like the outer regions of galaxy clusters, groups, or in isolation in the field. Early-type, gas-deficient, quiescent dwarfs (such as dwarf ellipticals, dwarf spheroidals, or ultra-compact dwarfs) are primarily found in high-density environments, e.g., in the vicinity of massive galaxies in groups and clusters. This morphology-distance or gas fraction-distance relation [53, 51] of the dwarf galaxies perpetuates the morphology-density relation observed for giant early-type and late-type galaxies (e.g., [122, 34]) and suggests that environmental effects may play an important role in shaping the evolution of dwarf galaxies (e.g., [151, 53]).

The best-studied dwarfs are the dwarf galaxies of the Local Group, which are sufficiently close to be resolved into individual stars and to even permit us detailed studies of their stellar content down to their oldest main-sequence turn-offs (see [112, 113, 58] for recent examples). All nearby dwarf galaxies studied in detail so far, regardless of their morphological type, contain very old stars with ages > 10 Gyr [52, 43, 30]. Though the fractions of these old populations vary and more massive dwarf galaxies usually show more extended episodes of star formation, old populations (i.e., early star formation) appear to be ubiquitous in dwarfs [52]. In low-mass galaxies the younger and/or metal-rich populations tend to be more centrally concentrated (e.g., [47, 61, 163, 54, 26, 97, 98, 82, 27, 74, 158]). Similarly, more metal-rich, younger populations tend to be dynamically colder than older, more metal-poor populations (e.g., [148, 7, 62, 8]), though not all dwarf galaxies show such population gradients (e.g., [84, 85, 150]).

Taking advantage of the wealth of information available for nearby, low-metallicity dwarf galaxies and their identifiable, metal-poor old populations, they will be in the focus of this review (although we will also consider galaxies beyond the Local Group). Many of the Local Group dwarf galaxies are even close enough for detailed spectroscopic abundance analyses of individual member stars, revealing not only the overall metal content, but the star-to-star variations in light and heavy elements of different nucleosynthetic origin (e.g., [3, 6, 23, 24, 31, 59, 67, 74, 75, 83, 86, 87, 88, 118, 136, 140, 141]), which in turn allow us to draw inferences about the conditions under which these metal-deficient galaxies and their stars formed.

2. METAL-POOR GALAXIES ALONG THE METALLICITY-LUMINOSITY RELATION

As pointed out by [145], star formation and molecular gas are closely related, and the ability to form molecular gas depends on metallicity (including the presence of dust to provide shielding). These authors argue that in the absence of metals, molecular gas
cannot easily form, leading to a long gas consumption time scale, a low star formation efficiency, and slow enrichment. Above a critical metallicity threshold, however, both star formation rate and enrichment accelerate, resulting in a rapid increase in stellar mass and metallicity [145]. Thus, without significant pre-enrichment by Population III stars, one would not expect to observe a continuously occupied metallicity-luminosity relation, but instead to see a bimodality inmetallicity [145].

Instead, the metallicity-luminosity relation for dwarf galaxies smoothly extends the correlation found for giant galaxies all the way down to ultra-faint dwarf spheroidal galaxies with luminosities as low as $M_V \sim -3$ mag [110]. Particularly for dwarf irregular and dwarf spheroidal galaxies, there is also an increasing “mean age” trend in the sense that the more metal-poor dwarf galaxies tend to be dominated by stellar populations with older ages (see also [128]; in contrast to the behavior seen in, e.g., giant elliptical galaxies). At optical wavelengths, the vigorously star-forming dwarf galaxies discussed in the next paragraph differ from this trend. Generally, the scatter in the metallicity-luminosity relation increases with decreasing luminosity ([110]; see also [124]).

### 2.1 Blue Compact Dwarf Galaxies

Metal-deficient star-forming dwarf galaxies, in particular blue compact dwarfs (BCDs), appear to be too luminous for their low metallicities [91, 77], thus deviating from the mean locus of dwarf galaxies in the metallicity-luminosity relation. Their apparent overluminosity is likely largely an effect of the pronounced starbursts they are undergoing at the present time. The analysis of the light and heavy element content of H II regions in such metal-poor BCDs and the low dispersion of the resulting element abundance ratios suggests a probable primary origin of these elements in massive stars [64]. This used to be considered an argument in favor of these galaxies being “young” in the sense that they are now undergoing their first burst of star formation (e.g., [64]).

The most metal-deficient BCD known, I Zw 18, which has a metallicity of only $Z \sim 1/50$, has often been considered an epitome of a truly young galaxy in the present-day Universe. *Hubble Space Telescope* (HST) photometry of resolved stars in I Zw 18 seemed to support the “young galaxy” scenario, since those data showed no trace of an older red giant branch (RGB) population [65]. Even deeper HST photometry, however, revealed that I Zw 18 is more distant than previously assumed and contains a well-defined RGB, demonstrating that this extremely metal-poor galaxy is not primordial [4].

More generally, recent studies of the integrated light have confirmed that BCDs are old systems currently experiencing starbursts (e.g., [164]). The stellar mass-weighted ages were found to be as old as up to 10 Gyr, while the luminosity-weighted ages are of the order of only 10 Myr [164]. The current star formation rates exceed the averaged past star formation rates by factors of more than two to three [164]. The colors of BCDs are best reproduced when invoking continuous star formation and a recent burst [165], although theoretical chemical evolution models also suggest series of bursts in combination with metal-enhanced winds [161]. Observational data suggest that the strongly enhanced star formation activity of BCDs is often caused by mergers or interactions with a companion, whereas one possible mechanism to halt the burst activity are supernova-driven winds...
Theoretical models support gas-rich dwarf-dwarf mergers, whose old populations turn into diffuse low-surface-brightness components [9]. The starbursts in the compact cores of BCDs may be fueled by low-metallicity gas from the outer extended gas disks of the progenitor dwarfs, resulting in metal-poor young stars [9].

### 2.2 Tidal Dwarf Galaxies

Tidal dwarf galaxies are long-lived, gravitationally bound objects free of dark matter that form from “recycled”, mainly gaseous material previously torn out during interactions between massive (spiral) galaxies (see [13] and references therein). The most massive tidal dwarfs are believed to form from matter concentrations at the tips of tidal tails and will experience starburst activity comparable to that of BCDs [13].

Tidal dwarf galaxies also deviate from the metallicity-luminosity relation. At a given luminosity, their metallicity exceeds that of regular dwarf galaxies since they are metal-rich already “at birth”, forming from the pre-enriched gas of much more massive galaxies [36]. In fact, their average metallicity (1/3 solar) is essentially independent of their absolute luminosity [36]. The star formation efficiency in tidal dwarfs resembles that of spiral galaxies [15]. This may be attributed to the improved self-shielding due to their higher-than-normal metallicities (as compared to other dwarf galaxies), facilitating the formation of molecular gas and star formation [15]. HST imaging suggests that the tidal dwarf candidates in the M81 group contain young stars formed in situ, but also older RGB stars that may have formed in the massive galaxies of this group [104, 32].

While too high a metallicity for a given luminosity is a good indicator for young tidal dwarf candidates, it is more difficult to identify old tidal dwarfs. Depending on when they formed, these objects may be as metal-poor as “normal” dwarf irregulars [60].

### 2.3 Dwarf Irregular and Dwarf Elliptical/Spheroidal Galaxies

In contrast to the previously discussed dwarfs (Sections 2.1 and 2.2), dwarf irregular (dIrr), dwarf elliptical (dE), and dwarf spheroidal (dSph) galaxies typically follow a well-defined metallicity-luminosity relation (see, e.g., [110]). dSph galaxies usually host prominent old populations [52], and the mean metallicities of these systems are thus dominated by the metallicities of their (old and intermediate-age) RGB populations. dIrrs, on the other hand, have typically experienced continuous star formation with some amplitude fluctuations [149]. This mode of extended periods of star formation interrupted by quiescent phases is also called “gasper” star formation [22]. That the (predominantly old) dSphs follow the same global metallicity-luminosity (or metallicity-stellar mass) relation as the dIrrs suggests that the dSphs did not experience substantial tidal stripping despite their proximity to massive galaxies [41]. Moreover, with the exception of dSphs that are currently being disrupted, their structure and kinematics do not show evidence of their being unbound tidal remnants (e.g., [121, 76, 40, 35, 156]).

A closer investigation of the metallicity-luminosity relation reveals that there is an offset between dSphs and dIrrs (e.g., [133]), which persists even when limiting the
comparison to the metallicities of the old populations in the two types of dwarfs [53].
Despite their older mean ages, dSph galaxies are more metal-rich than expected from
their luminosities, which may imply that they experienced initially more vigorous star
formation and enrichment than the slowly evolving dlrrs [53]. At a given stellar mass,
the metallicities of dSphs are typically higher by a factor of three than those of dlrrs
[160]. This makes it difficult for dlrrs to evolve into dSphs if their star formation were to
cease since mere passive fading would require more than a Hubble time, though such an
evolution appears to be possible for low-luminosity transition-type dlrr/dSph galaxies
[53]. DSphs and dlrrs may thus be intrinsically different and formed under different
conditions [53]. Alternatively, dSphs may have lost a large amount of their initial mass
due to later tidal (e.g., [90]) and/or ram pressure stripping (e.g., [53]) while allowing the
galaxies to survive as dark-matter-dominated bound entities (e.g., [159] and Sect. 3).
The low-luminosity end of the metallicity-luminosity relation consists exclusively of
the recently discovered faint and ultra-faint ($M_V < -8$ mag) dSph galaxies around the
Milky Way and M31 (e.g., [1, 11, 55, 109, 108, 132, 157, 166, 167, 168, 169]). The
ultra-faint dSphs are not only of interest for the cosmological substructure or missing
satellite problem (e.g., [89, 101, 147]), but are also intriguing objects from the point of
view of galaxy evolution: They are the least massive, least luminous, most metal-poor,
dark-matter-dominated galaxies known. As objects containing only old, metal-deficient
stars, they may be potential “pre-re-ionization fossils” [2, 14, 45, 101, 134, 123].

3. RE-IONIZATION AND LATER ENVIRONMENTAL EFFECTS

Environment, i.e., the local galaxy density, the degree of proximity to massive galaxies,
the degree of activity in massive galaxies, and immediate galaxy interactions, affect
the evolution and properties of low-mass galaxies. The earlier mentioned morphology-
density relation is a prominent example of the impact of environment. One of the
intriguing questions in this context, particularly with respect to dwarf galaxies, is the
importance of a galaxy’s intrinsic properties (“nature”) vs. the importance of external
influences (“nurture”). Clearly, both play a role in shaping dwarf galaxies in groups and
clusters (e.g., [5, 25, 28, 29, 33, 42, 99, 100, 68, 69, 70, 71, 72, 126, 128, 162]).
In the Local Group and other nearby groups, early-type companions with H I masses
below $10^6$ M⊙ are usually found within ~ 300 kpc around massive galaxies, whereas
late-type dwarfs with $M_{HI} > 10^7$ M⊙ are mostly located at larger distances [53, 46].
Low-mass transition-type dlrr/dSph galaxies fill the range in between these properties
[53]. This seems to suggest that gas removal caused by various processes related to the
proximity to massive galaxies may be the cause for the morphological segregation (see
also [151, 152]), in particular ram-pressure stripping, although the present-day Galactic
halo gas densities appear to be too low [53].
Cosmological simulations taking into account gas cooling, star formation, supernova
(SN) feedback, enrichment, and ultraviolet heating lead to satellite galaxies of which
95% are gas-free at the present time [139]. According to these simulations, satellites
need total masses of at least $5 \cdot 10^9$ M⊙ in order to retain their gas. Interestingly, also
isolated dwarf galaxies are predicted to be largely gas-deficient at the present time if
their total masses are below ~ $10^9$ M⊙ [139]. These authors conclude that while gas
stripping aids in removing gas from dwarf satellites, the total mass of a dwarf galaxy (thus an intrinsic property) is the primary factor determining whether a galaxy retains or loses its gas, and the total mass also governs a galaxy’s star formation and enrichment.

In contrast, other models advocate a stronger role of galaxian environment. For instance, in simplified models presented by [117], feedback-assisted ram pressure stripping or tidal stripping during the period when infalling dwarfs still experienced active star formation may have effectively removed the gas, reproducing the observed morphological segregation. [120] investigate the effects of re-ionization on satellite properties. They find that “external”, uniform re-ionization from the cosmic radiation field may have less of an effect than “internal”, distance-dependent re-ionization from the most massive Milky Way progenitor. Assuming that the satellites were already at similar distances as today, the photoevaporation driven by the Galactic radiation field first removed star-forming material from the inner satellites, allowing the outer ones to continue star formation for a longer period ([120]; see also [151]). This “internal” scenario can reproduce the observed cumulative radial satellite distribution very well, in contrast to a scenario that only considers the external ionization field [120].

[116] include four epochs of star formation in their simulations: (1) At \( z \sim 20 \) star formation occurs in systems large enough for H\(_2\) cooling resulting in very metal-poor stars, (2) later through H\(_1\) cooling (leading to re-ionization), (3) during re-ionization until \( z \sim 2 \) through further H\(_1\) cooling in subhalos that are large enough not yet to have lost their gas, and finally (4) during the last 10 Gyr through metal cooling. Ultra-faint dSphs with \( M_V > -5 \) then formed very early in low-mass halos via H\(_2\) cooling [116]. The H\(_2\) cooling threshold of \( M_{H_2} \sim 10^5 \) to \( 10^6 \) M\(_\odot\) implies a luminosity threshold, which excludes the existence of ever fainter satellites. Satellites in the luminosity range of \(-5 > M_V > -9 \) experienced star formation via H\(_1\) cooling and photo-heating feedback, whereas most of the stars in the brighter satellites formed after re-ionization [116].

4. CLUES FROM CHEMICAL ABUNDANCES

Dwarf galaxies do not represent a simple stellar population of a single age and metallicity. Instead, they usually experience extended episodes of star formation leading to gradual enrichment and, depending on duration of star formation, also to a measurable range of ages (e.g., [48, 52, 63, 107, 127]). For nearby dwarfs the spread in metallicity (and even in individual element abundance ratios) can be measured directly through absorption line spectroscopy of individual stars, particularly along the RGB. In more distant dwarfs, the brightest supergiants may still be accessible (e.g., [16, 146, 154]), while emission-line spectroscopy of planetary nebulae or H\(_\text{II}\) regions can be conducted over a wide range of distances (e.g., [78, 79, 80, 81, 95, 96, 102, 103, 130, 131, 153]).

4.1 Metallicity Distribution Functions and Gradients

Recent spectroscopic analyses of large numbers of RGB stars in nearby dwarf galaxies resulted in well-sampled metallicity distribution functions (MDFs) for many dSphs and dIrrs. Often these MDFs show a gradual rise toward higher metallicities and then a
steeper fall-off, but exceptions exist (e.g., [7, 8, 12, 13, 20, 21, 74, 83, 85, 86, 94, 118]). A G-dwarf problem (or, more accurately, a K-giant problem) is found in all dwarfs (e.g., [86]). A comparison of the MDFs with simple chemical evolution models generally shows a poor fit for closed-box models or pristine gas models, but better results for pre-enrichment, leaky box, or models with additional gas infall (e.g., [83, 74]). The range in stellar metallicity increases with galaxian luminosity (or stellar mass) [74]. The interplay between slow gas infall, low-efficiency star formation, and strong galactic winds can reproduce both the observed MDFs and element abundance ratios [93]. The pronounced decrease of the metal-rich end of the MDF is then caused by the removal of gas – without winds, the resulting MDF would be much more metal-rich than observed [93, 75]. Other models, however, do not require strong winds but employ external mechanisms for the loss of heated, enriched gas such as ram pressure or tidal interactions [106].

Shallow gradients of decreasing metallicity with galactocentric radius are commonly found in spectroscopic surveys [74], confirming the finding that more metal-rich and/or younger populations are more centrally concentrated and kinematically colder (see Section 1 and, e.g., [54]), although there are also exceptions (e.g., [85, 86, 150]). The lack of a gradient may be due to insufficient radial area coverage in spectroscopic surveys [74] or be caused by stripping (see [137]). Tidal stripping would primarily remove the more extended (and more metal-poor) stellar populations and homogenize the stellar radial velocities of the components [137, 150], on the other hand, point out the danger of overinterpreting small stellar samples in favor of the existence of a gradient.

A number of theoretical models have explored the possible origin of population gradients. For example, apart from SN-driven blow-outs SNe in the outer regions of dwarfs may drive inward-propagating winds that ultimately concentrate cold gas in the inner regions [114]. Star formation may re-start from this enriched gas [114], which would result in a metallicity gradient. Other models suggest that any gradients will be quickly erased since the winds of SNe II tend to homogenize the interstellar medium [106, 107]. Metallicity gradients are then introduced by the spatially inhomogeneous enrichment through the much rarer SNe Ia, which occur more frequently in the denser populated central regions [107, 125] show that the time scales of the change of the dark matter profiles of dwarf galaxies (from cuspy to cored profiles) due to feedback and the redistribution of (baryonic) matter on the one hand and of the formation of chemical gradients on the other hand may be linked. The oldest stars in the dwarf move on radial orbits, and inner and outer regions are thus well mixed (similar to [107], but due to a different mechanism). The evolving density profile implies that younger, more metal-rich stars forming in the central regions tend to be on more circular orbits with smaller radial velocity dispersion, resulting in less mixing with the outskirts [125].

4.2 Element Abundance Trends and Inhomogeneities

Dwarf galaxies exhibit considerable stellar abundance spreads. The range of metallicities often spans $>1$ dex in [Fe/H] even in galaxies dominated by old populations (e.g., [140, 38, 53, 118, 24, 92, 74]). In several dwarf galaxies studied in detail it turns out...
that at any given age there is a spread in metallicity (e.g., [44, 56, 57, 73, 79, 86, 118]). Moreover, at a given overall metallicity one tends to find scatter in the $\alpha$ abundance ratios (e.g., [87, 88, 3]). These galaxies were not well-mixed when these stars formed. The trends as such differ from galaxy to galaxy, confirming once again that no two dwarfs are alike – not even dwarfs of the same luminosity and morphological type [47].

There are a number of theoretical models addressing these issues. It seems that at very early times and very low metallicities star formation was governed by stochasticity and inhomogeneous heavy-element pollution caused by the few early SNe II [107]. Subsequently, with increasing enrichment, the feedback from these SNe led to fairly homogeneous mixing [107]. At higher metallicities, individual SNe Ia again led to localized inhomogeneous abundance patterns [107], resulting in a substantial element abundance spread even for coeval stars, just as seen in the observations (see also [125]).

Considering trends in $[\alpha/\text{Fe}]$ vs. $[\text{Fe/H}]$, stars in dwarf galaxies resemble those in the Galactic halo at low metallicity ($[\text{Fe/H}] < -2$ dex) (e.g., [24, 87, 92, 155]), but tend to show lower $[\alpha/\text{Fe}]$ ratios at higher metallicities as compared to typical Galactic halo stars (e.g., [140]). SNe Ia thus seem to contribute already at lower metallicities in dwarfs than in our halo. See [31] for a nice demonstration of the age dependence of the $[\alpha/\text{Fe}]$ vs. $[\text{Fe/H}]$ trend. The different locations of the “turn-over” from the near-constant $[\alpha/\text{Fe}]$ towards lower ratios appears to roughly depend on a galaxy’s stellar mass.

Lower (than Galactic) $[\alpha/\text{Fe}]$ ratios at a given $[\text{Fe/H}]$ may indicate (1) low star formation rates (with few contributions of $\alpha$ elements from SNe II), (2) a substantial loss of SN ejecta (metals) via galactic winds, or (3) a larger contribution from SNe Ia (enhancing the Fe content with respect to $\alpha$ elements) [140]. Several studies show evidence for early rapid enrichment based on heavy neutron-capture and r-process element abundance ratios (e.g., [3]), while low-efficiency, extended star formation with stochastic, inhomogeneous contributions from SNe Ia ejecta and asymptotic giant branch stars appears to have been important at higher metallicities (e.g., [3, 24, 38, 155]). Also, an initial mass function sparsely populated with massive stars due to the low star formation rate may contribute to the slow build-up of metallicity and to the inhomogeneities [87].

### 4.3 Extremely Metal-Poor Stars

Major efforts were devoted to the search for extremely metal-poor stars in our Milky Way and in nearby dwarf galaxies. While no stars as metal-deficient as found in the Galactic halo ([17] and references therein) have been detected in Galactic satellites yet, the current record holders have $[\text{Fe/H}] = -3.96 \pm 0.06$ dex in the dSph Sculptor [144] and $-2.67 \pm 0.33$ dex in the irregular Large Magellanic Cloud (LMC) [57].

Ultra-faint dSphs appear to be a particularly rewarding hunting ground for very metal-deficient stars as suggested by both observational data (e.g., [92, 118, 119, 142]) and simulations (e.g., [116, 138]). [142] and [88] argue that the abundance patterns in extremely metal-poor stars in the ultra-faint dSphs Leo IV and Hercules are consistent with enrichment through Population III SN explosions. According to simulations, ultra-faint dSphs may have experienced star formation via $H_2$ cooling of pristine gas at high redshift ([116]; Sect. 3), an inefficient process resulting in low star formation rates [138].
These strongly dark-matter-dominated galaxies themselves may be merger products of very early H$_2$-cooling minihalos \[138\], which may account for their metallicity spread.

While the element abundance ratios in dSphs were once considered an argument against a significant contribution of such galaxies to the build-up of the Galactic halo (see, e.g., \[39\] and references therein), this picture has changed recently. A number of studies point out the good agreement of the abundance ratios in metal-poor stars in the Galactic halo and in dSphs. This chemical similarity makes contributions from dSphs plausible and indicates that the early chemical evolution of galaxies on all scales may be similar (e.g., \[24, 37, 92, 119, 142\]).

Some models predict that most of the stars in the stellar halo (particularly the inner halo) were formed not in dSphs, but in a small number of massive dIrr-like galaxies that then were accreted by the Milky Way some 10 Gyr ago \[135\]. The element abundance ratios in genuinely old, metal-poor field and globular cluster stars in the Magellanic Clouds turn out to be in good agreement with Galactic halo abundances \[66, 115, 57\]. These findings are compatible with the predicted early accretion of dIrrs.

Ultra-faint dSphs, on the other hand, may be a very important source of extremely metal-deficient stars in the Galactic halo. Intriguingly, and contrary to earlier views, these galaxies may even contain too many such extremely metal-poor stars as compared to the Galactic halo \[92, 143\]. However, as emphasized by \[92\], most halo star studies focused on the inner halo. Carbon-enhanced metal-poor (CEMP) stars may serve as a tracer for generally very metal-poor stars, and their number increases with decreasing metallicity and with height above the Galactic plane \[18\]. In the outer halo the fraction of CEMP stars is approximately twice as much as in the inner halo \[18\]. Hence we may expect also a larger (yet to be detected) number of extremely metal-poor stars there.

Combining these findings and arguments, a picture emerges where the inner halo may consist largely of stars contributed early on by larger progenitor systems (which make it difficult to uncover dSph contributions), while the outer halo may plausibly contain a significant stellar component accreted from small dwarfs such as dSphs \(92\); see also \[10\]). Clearly, detailed element abundance information for more old stars in the outer halo, in the Magellanic Clouds, and in ultra-faint and classical dSphs is desirable to explore the importance of early accretion and of the origin of very metal-poor stars.

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