Chemical and stellar properties of early-type dwarf galaxies around the Milky Way

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Early-type dwarf galaxies (ETDs) are the end-points of the evolution of low-mass galaxies whose gas supplies have been extinguished. The cessation of star formation lays bare the ancient stellar populations. A wealth of information is stored in the colours, magnitudes, metallicities and abundances of resolved stars of the dwarf spheroidal and ultrafaint galaxies around the Milky Way, allowing their chemistry and stellar populations to be studied in great detail. Here we summarize our current understanding, which has advanced rapidly over the past decade owing to flourishing large-scale astrometric, photometric and spectroscopic surveys. We emphasize that the primeval stellar populations in ETDs provide a unique laboratory for studying the physical conditions on small scales at epochs beyond redshift \(z = 2\). We also highlight the observed diversity of star-formation and chemical-enrichment histories in nearby dwarfs. These data cannot yet be fully deciphered to reveal the key processes in dwarf evolution, but the first successful attempts to pin down the sites of heavy-element production have been made.

ETDs are typically satellites of larger galaxies—about 50 ETDs are known around the Milky Way, with perhaps hundreds more within the virial radius that are either unconfirmed or remaining to be discovered.

The appeal of ETDs is twofold. First, they represent the final stages of the complete evolution of a galaxy, thus offering a chance to benchmark our models of SF, chemical evolution and feedback in relatively uncomplicated settings. Second, being the weakest galaxies in terms of their ability to retain gas, ETDs host the least enriched stellar populations, opening a window onto the earliest and most primitive stars. Beyond a megaparsec from the Sun more numerous and representative samples of dwarfs are available, but none with as detailed a view of their denizen stars as the resolved local ETDs.

In the remainder of this section, we first sketch the life story of the ETDs, emphasizing their primitiveness and susceptibility to environmental effects. We compare their properties to both recent interlopers (the SMC and LMC) and the destroyed dwarfs that built the stellar halo, such as the Gaia Sausage. The 'Generic trends in the Milky Way ETDs' section summarizes generic trends in the SF histories (SFHs) and metallicities of ETDs, which bear the marks of their life story. Finally, the 'Nucleosynthetic trends' section describes the evidence from abundances that pins down the early history of ETDs.

\[L_{\odot} < M_{\odot} < 10^7 \text{M}_\odot\]

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Connection between ETDs and late-type dwarfs. ETDs are simple in appearance: they (usually) have spheroidal shapes and smooth stellar light distributions, lack large quantities of hydrogen and do not show any recent SF activity. They are antithetical to the late-type dwarfs (LTDs), which are gas rich and often have irregular shapes that bear signs of ongoing SF. The dichotomy between LTDs and ETDs, just like that of the more massive early- and late-type galaxies, relates to the distinction between life (that is, the active conversion of gas into stars and the associated chemical enrichment and feedback) and death (that is, shutting down of SF and subsequent collisionless relaxation driven by gravity alone). The ETDs are simply the lifeless descendants of the LTDs\(^1,2\). The intimate connection between the two types of dwarf galaxy is revealed by the continuity of their structural properties. This link is less perceptible.
around the Milky Way owing to the dominance of quenched dwarfs, but is well established around more distant hosts and in galaxy agglomerations.

The appearance of a galaxy that is star-forming (or alive) is determined, in the absence of strong environmental effects, by the state of its interstellar medium (ISM) and the mode of its SF. Bursty SF leads to irregularly shaped and clumpy galaxies, whereas steady SF rates are hosted by well-behaved disks. The shallow potential wells of low-mass dwarf galaxies cannot easily contain highly energetic feedback processes such as supernovae (SNe), leading to irregularly shaped and clumpy galaxies, whereas steady SF leads to regular in shape with no prominent small-scale stellar substructure. The two late-types—the SMC and LMC—are comparable in size to Antlia 2, but ~8 magnitudes brighter. These two have luminosities similar to the faintest classical dwarfs and UFDs are better separated at constant size.

Milky Way dwarfs were made early. In view of this, it is not surprising that the majority of dwarf galaxies inside the Milky Way’s virial radius (~200 kpc) have been transformed. In comparison with the two most massive satellites, the LMC and SMC, the rest appear regular in shape with no prominent small-scale stellar substructure, although the Sagittarius and Fornax dSphs do possess globular clusters. They have no detectable amount of hydrogen and the last cinders of their SF have been extinguished. The recent astrometric data from the European Space Agency’s Gaia satellite delivered confirmation that these galaxies had started their transformation early. For a few satellites, some ambiguity in their orbits still exists due to our ignorance of the temporal evolution of the potential of the Milky Way at distances exceeding 100 kpc. However, most of the Galactic ETDs arrived at their current host many billions of years ago. The SMC and LMC are a very recent accretion, which explains their irregular shapes, active SF and substantial gas reservoirs.

The accretion histories of the Milky Way satellites are intimately connected to their SFHs. Due to their proximity, their light distributions are resolved into individual stars. This permits the construction of detailed colour–magnitude diagrams (CMDs) with just a moderate amount of mostly foreground contamination (early examples are presented in refs. [29–31]). Stellar distributions in the CMD can be modelled to infer the build-up of stellar mass as a function of age and metallicity. This reveals that their stellar populations are dominated by ancient and metal-deficient stars. Some higher-mass ETDs managed to hold on to some of their gas for a while and continued to form stars at intermediate ages (4–8 Gyr), and thus display complex SFHs. The temporal resolution of the CMD-based SFH models deteriorates with look-back time as the spacing of the models in the CMD space starts to shrink; it is approximately 0.1–0.2 Gyr at an age of 1 Gyr and drops to 1–2 Gyr for stars older than 8–10 Gyr (ref. [32]), although relative ages at a resolution of 0.5–1 Gyr are possible for ancient populations. It is not feasible to track short-timescale variations in early SF activity predicted by the theoretical works discussed above, but it is possible to resolve later modulations in the SFH, typically associated with the infall and ensuing interaction with the Milky Way.

The prevalence of ancient stellar populations in the ETDs presents a unique opportunity to study physical conditions that underpinned structure formation and chemical enrichment on small scales in the early Universe; that is, beyond z = 2. Observationally, the combined effects of the dark-matter halo growth regulated by the baryonic feedback are summarized by a relation between the galaxy’s baryonic mass M and the dark-matter mass M._vir (refs. [33,34]). Although the total stellar mass is available directly from observations, the total dark-matter mass must be inferred via abundance matching or dynamical modelling. At the range of the halo masses occupied by ETDs, the relative strength of the baryonic regulation of galaxy formation reaches its maximum, leaving many of the low-mass dark-matter haloes completely devoid of stars. The marked decrease in the efficiency of galaxy formation at low M_* can be analysed to infer: (1) the steepness of the M_*–M._vir relation, (2) the...
amount of scatter in stellar mass at a given dark-matter mass, and (3) the lowest dark-matter halo mass to host a galaxy. These phenomenological descriptors can then be linked to the underlying physics of the early Universe. For example, the change in the slope of $M_\bullet - M_{\rm vir}$ curve can be connected to the impact of cosmic reionization. Much of the evolution of the $M_\bullet - M_{\rm vir}$ relation at the low-mass end (for example the increased steepness and scatter at $M_{\rm vir} \lesssim 3 \times 10^9 M_\odot$) can be explained by the detrimental effects of UV heating of the gaseous intergalactic medium during reionization.

The reduced SF activity in the nearby ETDs enables us to understand the details of the synthesis and delivery of heavy elements in SN explosions and neutron-star mergers. Compared to the field, it is easier to find a primitive star (that is, one formed from the gas enriched by a small number of previous stellar generations) in a spectroscopic follow-up campaign. More importantly, the chemical evolution of ETDs is straightforward to interpret. Small galaxies quickly finish accreting fresh gas and for the rest of their lives recycle the fuel acquired early. Thus, distributions of chemical abundances form tight and recognizable sequences that can be modelled. For instance, the relative contributions of different kinds of polluter (including poorly constrained exotic types) can be inferred and the yields of individual elements contributed by particular types of SN pinned down.

One example of such a pattern is the evolution of the ratio of the $\alpha$-element abundance (such as O, Mg, Si) to that of iron, Fe. As the ETD starts to form stars, [$\alpha/Fe$] values stay elevated (high plateau) but begin to decrease noticeably later in its evolution, as shown in Fig. 3a. This characteristic plateau + knee [$\alpha/Fe$] pattern is due to the change in relative contribution by core collapse SNe (CCSNe) and type Ia SNe. The two types of SN show distinct [$\alpha/Fe$] behaviour due to (1) differences in the mechanism of heavy-element dispersal during the explosion (the heaviest elements end up locked in compact remnants after CCSNe, whereas much (if not all) of the white dwarf is destroyed during type Ia SNe) and (2) time delays between the SF and the SN explosion (massive stars, the progenitors of CCSNe, collapse on the order of 10–20 Myr, whereas it takes on average ~1 Gyr for a stellar binary to produce a white dwarf that can explode as a type Ia SN).

For elements heavier than Fe there exist two principal nucleosynthetic routes that both require the capture of neutrons onto heavy (for example, Fe) seeds but differ in neutron flux densities. The so-called slow (s)-process operates at low neutron densities, whereas at high neutron densities, the rapid (r)-process takes over. The astrophysical site of the s-process has been identified with the asymptotic giant branch stars, whereas the exact origin of elements produced in the r-process is still debated. It may take place in CCSNe, including magnetorotational explosions, or it may need rarer but more efficient mergers of two neutron stars (or a neutron star and a black hole).

**Ghost of the dwarfs long gone.** The Milky Way’s stellar halo is built from earlier-accreted dwarf satellites. This provides a rich repository for investigating the chemical and stellar population properties of small galactic systems long gone. With wide-area spectroscopic surveys and the astrometry from Gaia it is now possible to unscramble the tidal wreckage and reassemble the disrupted satellites. The stellar debris can find its way close to the Earth via phase mixing. These bright stars are perfect targets for spectroscopic follow-up campaigns, offering an unprecedentedly high-resolution and high-signal-to-noise-ratio view of their progenitor’s chemical abundance patterns. The destroyed systems are not expected to be identical to the ETDs that survived to the present day. Nonetheless, the local ETDs are the obvious point of comparison because they too had their SF activity shut down a relatively long time ago. The destroyed dwarfs experienced SF cessation at different points further in the past, so on average their stellar populations should be more primitive. Spectroscopic studies of the stellar halo suggest that it contains relatively more metal-poor stars than the massive, classical dSphs, although this may in part be due to an incorrect metallicity analysis for stars below $[\text{Fe/H}] \approx -3$ (ref. 125). The halo’s metallicity distribution function is also more mixed and it contains an unexpectedly large number of high [$\alpha/Fe$] abundance stars at high metallicity compared with the dSphs. Over the past 15 years, a vast population of low-luminosity UFDs was uncovered with photometric sky surveys. Disrupted UFD systems may well be the principal contributors to the metal-poor end of the stellar halo (see the discussion in ref. 134). At the metal-rich end, both the homogeneity and the higher SF efficiency (higher $\alpha$-element abundances) of the halo stars are due to the dominance of the tidal debris of the ancient massive merger predicted by ref. 116 and discovered using Gaia data (the disrupted galaxy known as the Gaia Sausage or Gaia Enceladus), see refs. 136–138; ref. 139 traces the history of the idea. Stars in the Gaia Sausage are older than 10 Gyr (ref. 140) and possess a chemical signature with low Mg/Fe and Ni/Fe. The highest [$\alpha/Fe$] abundances in the local halo are contributed not by accreted satellites, but instead by the splashed prehistoric disk of the Milky Way itself.

**Generic trends in the Milky Way ETDs**

**SFHs.** SFHs provide a chronology of how the Milky Way ETDs assembled their present-day stellar masses. The more massive dSphs usually possess multiple populations that differ in age, metallicity and kinematics. Their SFHs are bimodal and episodic. For example, using CMDs built from deep Hubble Space Telescope (HST) photometry, ref. 142 showed that the Fornax dSph had a major SF episode at early times, a second strong burst about 5 Gyr ago and recent intermittent episodes from 2–0.2 Gyr ago. Mergers or interactions have been suggested as a probable cause of its spasmodic SFH. There is also evidence of tidally induced SF, as the intermediate-age and young SF events may correspond with pericentric passages of its orbit around the Milky Way. The Carina dSph provides another clean example of an episodic SFH. This is evident from its CMD, which shows at least three different main-sequence turn-offs. Carina had at least three major SF episodes, one at old times (>8 Gyr ago), a second at intermediate ages (4–6 Gyr ago), continuing into even more recent activity (2 Gyr ago). Using both wide-field photometry and spectroscopic data, ref. 143 found that about 60% of the stars in Carina formed in the episode at intermediate ages. The populations in Carina are substantially more mixed than Fornax—as indicated by the small differences among their characteristic half-light radii or velocity dispersions. The Sculptor dSph presents a less extreme example of multiple populations. It experienced a single SF event limited to approximately the first 1–2 Gyr after the Big Bang, producing about 70% of its stars. However, it continued to form stars in its central parts after the epoch of reionization, leading to a centrally concentrated, more-metals-rich population. In the outer parts, the stars are overwhelmingly metal poor and probably formed during the reionization epoch, or soon after its end. The kinematics of multiple populations in dSphs helps constrain the structure of their dark-matter haloes, specifically whether the central density is cored or cusped. The less-massive dSphs do not possess multiple stellar populations. For example, Sextans presents an almost a flat [Fe/H] radial distribution from the spectroscopic measurements conducted in ref. 157, indicating a SF burst shorter than ~1 Gyr. Using deep Suprime-Cam photometry, ref. 158 argued that the Sextans dSph stopped forming stars about 13 Gyr ago, close to the end of the reionization epoch. Likewise, the stellar population of Draco dSph is mainly old. Although there is an intermediate-age population in Draco, most of the SF (up to 90%) took place before ~10 Gyr ago, with no SF activity detectable in approximately the past 2 Gyr (ref. 158). In the Ursa Minor dSph, virtually all the stars formed earlier than 10 Gyr ago.
and 90% formed more than 13 Gyr ago (ref. 166). The SF in dSphs halts via three mechanisms: (1) cosmic reionization, (2) SN feedback associated with the early SF epoch in the dwarf galaxy itself and (3) ram-pressure stripping and tidal interactions with a nearby larger galaxy. The relative importance of each contribution is unclear.

The least massive of all the ETDs are the UFDs. They are almost wholly composed of very ancient stars. Even Crater 2, one of the most luminous UFDs, has relatively old populations on average (that is, older than 10 Gyr), while showing signs of relatively extended SF (refs. 164, 165). UFDs typically have SFHs where >75% of the stars formed by 

M/M_⊙ ≳ 75% of the stars formed by

< 10 Gyr ago) and 100% by 

< 3 Gyr ago). This is consistent with the picture that SF in these smallest dark-matter sub-haloes was suppressed by the reionization of the Universe. Some differences do seem to be present among the UFD population. For example, UFDs associated with the SMC and LMC show quenching times about 600 Myr more recent than those of other Milky Way UFDs, although the differences are probably within the errors (refs. 164, 165). Eridanus II is a UFD located close to the Milky Way's virial radius. In the study reporting its discovery (ref. 162), there were what turned out to be misleading hints of young- or intermediate-age populations. With deeper HST/Advanced Camera for Surveys CSMs reaching the oldest main-sequence turn-off, we now know that Eridanus II formed the bulk of its stars in a very early and extremely short (<500 Myr) burst (ref. 164). By estimating the number of SN events and the corresponding energy injected into the ISM, Eridanus II could have been quenched by SN feedback alone.

Metallicities. The chemical properties of ETDs go hand in hand with their SF activity: larger accumulated stellar masses (more extended SFHs) correspond to higher average metallicities (computed using a representative sample of stars in the galaxy).

A correlation exists between the stellar mass or luminosity of a dwarf galaxy and its mean metallicity. Data for the Milky Way satellites are shown in Fig. 2, together with an empirical fit from ref. 162. The mass–metallicity relation is well established for both gas-phase (refs. 161, 162) and stellar (refs. 163) abundance estimates across a wide range of galaxy masses. The shape of the correlation is close to linear for galaxies with masses lower than 10^10 M_⊙, but starts to flatten beyond that. The evolution of the shape as a function of galaxy mass indicates that there are multiple competing physical processes at play (such as gas and metal flows in and out of the galaxy).

Both ETDs and LTDs around the Milky Way lie on the same linear mass–metallicity relation (ref. 162). Over recent years, the range of masses 10^0 < M/M_⊙ < 10^10 has been enlarged by the UFDs, broadening the metallicity spread at fixed mass and extending the range to even fainter systems with ~10^9 M_⊙. There is evidence of a floor in the mean stellar metallicity in the low-mass regime (ref. 46). Although the increased metallicity spread can be accounted for by the differences in the amount of tidal stripping the galaxy can incur at fixed observed stellar mass, the flattening of the mass–metallicity relation at low masses is not fully reproduced in current numerical simulations (refs. 175–177).

Characterizing an entire galaxy with an average metallicity value is an oversimplification. Despite ETDs and LTDs occupying the same continuous mass–metallicity relation, in detail, their individual [Fe/H] distributions are distinct (ref. 68). Metallicity distribution functions (MDFs) of LTDs are consistent with ongoing SF activity, whereas the MDFs of the brightest ETDs show a sharp cutoff at high metallicity, indicative of the abrupt removal of their gas and rapid shutdown of their SF. These MDF differences may pose a problem to the current theory in which dSphs are simply LTDs transformed by their interaction with the Milky Way. To understand the roles that feedback and ram pressure play, it is crucial to reconstruct and compare their SF and orbital histories (ref. 46). Even after the complete shutdown of SF, the dwarf’s past SF rate can be gleaned from the metallicity of the α knee (Fig. 3), which indicates how much self-enrichment has happened on the timescale corresponding to the onset of type Ia SNe.

Fig. 2 | The (stellar) mass–metallicity relation for Milky Way satellites.

The colour coding is the same as in Fig. 1 using data from ref. 162. The sizes of the circles are proportional to the width of the metallicity distribution. Tidally stripped satellites evolve downwards, as shown by the arrow. The grey band shows the fit to all Local Group dwarfs proposed in ref. 166, which holds over a range of >10 magnitudes.

Among the classical dSphs, the satellite’s luminosity (and therefore total stellar mass) correlates reasonably well with the metallicity of the α knee (for example, refs. 96, 162, 176), but this pattern is broken for the two largest satellites: the LMC and the SMC (ref. 178). In these massive dwarfs, the contribution of type Ia SNe is shown to dominate Fe production at metallicities much lower than expected. Using the most recent APOGEE data, ref. 179 not only confirmed the results of ref. 178 but also revealed that the LMC and SMC both experienced a late uptick in α-element abundances symptomatic of a recent burst of SF. The early SF inefficiency and the subsequent SF activity may be linked with the particular orbital evolution of the SMC and LMC (that is, residing in a distant low-density environment before falling into the Milky Way recently). Another massive satellite galaxy now experiencing a tidal interaction with the Milky Way, the Sgr dwarf, shows a more metal-rich α knee and is consequently inferred to have had a stronger SFH than either of SMC or LMC (refs. 176, 179, 180).

Nucleosynthetic trends

The mutation of LTDs into ETDs is accompanied by gas loss and the cessation of SF. Proximity to a large galaxy around the time of formation leads to ram-pressure stripping of the dwarf’s gas, truncating its SF activity. Ref. 181 used SF histories of local dwarfs to propose two types of dSph: slow and fast. The fast ones are born in high-density environments and form their stars early, whereas the slow ones stay away from big galaxy concentrations and thus extend their SFHs. Classification into fast and slow dwarfs is, however, ambiguous. Both Fornax and Sagittarius started with a SF burst, but continued to form stars later on, despite residing not too far from the Milky Way (ref. 179). Note that the ram pressure is not the only means of unbinding the gas from the dwarf; this can also be done by feedback from SN explosions (ref. 182).

In the past decade, progress in assembling large homogeneous spectroscopic samples (for example ref. 183) has been matched by...
efforts to develop flexible chemical evolution models to interpret the data. According to the models, the gas outflow rate is discernible from the evolution of the α abundances with metallicity: stronger gas ejection makes the knee steeper (see fig. 3 of ref. 184).

However, observational evidence for knees in α-element trends with metallicity is mixed. For instance, in analysing eight of the Milky Way dSphs, ref. 183 found no strong evidence for a knee sample limited to [Fe/H] > −2.5. All eight galaxies exhibit similar mean tracks in all four α elements considered. No clear plateaus are visible, though most tracks do show change in steepness at intermediate [Fe/H]. In a follow-up study, ref. 96 detected hints of α knees in several dwarfs, all at low metallicity ([Fe/H] < −2). Dwarfs consistently fail to hold on to the metals they make, even if the physics of gas ejection is poorly understood.

It has so far been securely established that the chemical evolution of dwarfs largely depends on their stellar masses (see for example refs. 177, 183, 185), but the details of gas inflow and outflow remain muddled by uncertainties in the theoretical yields and SN rates, as well as the physics of gas ejection. This inspired many recent efforts exploiting medium- and high-resolution spectroscopy to constrain the properties of the stellar explosions that govern the chemical evolution of galaxies. Motivated by this, we focus on chemical results emerging from fresh high-resolution studies aiming to pin down the sources of heavy-element production.

**Extremely metal-poor stars.** The lowest-metallicity stars are unique tracers of the first bouts of chemical enrichment in the young Universe and as such have been vigorously hunted down both in the Milky Way and its satellites. Using the demarcation suggested by ref. 193, extremely metal-poor (EMP) stars are those with Fe abundances below 1/1,000 of Solar values, or [Fe/H] < −3; that is, similar to the metallicities of metal-poor damped Lyman-α systems. Early studies of EMPs revealed that at low metallicities, the fraction of the carbon-enhanced metal-poor (CEMP) stars dramatically increased. CEMP stars come in a number of flavours. CEMP-s (or CEMP-r/s) stars exhibit overabundance of s-process (or r- and s-process) elements, respectively. They make up around 80% of all CEMP stars. The favoured production channel of CEMP-s stars is mass transfer of carbon and s-process material from the envelope of an asymptotic giant branch star to its (presently observed) binary companion. CEMP-r/s stars originate in their natal gas clouds enriched by early SNe. CEMP-no stars exhibit no strong neutron-capture-element enhancements and are preferentially found at the lowest metallicities. Possible progenitors for CEMP-no stars include massive stars with [Fe/H] < −6, which models suggest have greatly enhanced abundances of C, N and O.

The EMP/CEMP stars are linked to the bigger question of the properties of Population III stars—that is, those first, presumably metal-free, objects that seeded structure formation and chemical evolution in the Universe. Although the CEMP stars observed today are not representatives of this primordial population, some of them may be the direct descendants of Population III.
A number of EMP stars have been identified in the classical dSphs, such as Sculptor, Fornax and Sagittarius207–212, yet the low-[Fe/H] wing of the distribution in ETDs is still weaker than that of the Galactic halo. Two recent developments have helped to reconcile the MDFs of the field and the satellite stars. First, the UFDs exhibit appreciable metallicity spreads and their mean Fe abundances are an order of magnitude lower than the classical dSphs. As is evident from their SFHs, the UFDs contain a larger proportion of metal-poor and EMP stars213,213. Although carbon production channels in the early Universe operate in all galactic environments (stars with high carbon abundances are found in the Milky Way, dSphs and UFDs), the fraction of CEMP stars in UFDs is nearly ten times higher than in dSphs214,215,216. Secondly, using Gaia Data Release 2 proper motions, refs. 215,216 demonstrated that the orbits of over a quarter of all field stars with $\mathrm{[Fe/H]} < -4$ are prograde and concentrated within 3 kpc of the Galactic plane. One explanation is that these ultra-metal-poor stars were formed in the early disk and were kicked up by subsequent mergers217,218,219. Alternatively, according to ref. 219, these EMP stars could represent a kinematically biased sample of stars born in the ancient hot, messy, pre-disks Milky Way characterized by highly stochastic SF and chemical enrichment.

Not all of the most-metal-poor stars in the Milky Way are rich in carbon. A handful of metal-poor but carbon-normal stars have been discovered in the halo203,204,205 prooving formation channels in the early Universe distinct from their carbon-rich counterparts. The lowest-carbon-abundance metal-poor star was discovered220 in the Sculptor dSph. This star is surprisingly different from the bulk of the carbon-normal stars in the halo: at $\mathrm{[Fe/H]} \approx -4$, it shows a markedly non-uniform $\alpha$-element abundance composition. For example, at low $\mathrm{[Mg/Fe]}$, high $\mathrm{[Ca/Fe]}$ and $\mathrm{[Ti/Fe]}$ are observed. Ref. 220 compared their measured abundances of C, Na, Mg, Al, Si, Ca, Sc, Ti, Cr, Mn, Co and Ni to theoretical models and determined that the best fit was produced by an enrichment pattern seeded in a hypernova explosion of a $20 M_\odot$ zero-metallicity star. This is one of the best candidates for a descendant of a massive, metal-free Population III object.

**Progenitors of type Ia SN explosions.** Type Ia SNe have been used to demonstrate that the expansion of the Universe is accelerating222,223. However, the physics behind their use as standard candles remains obscure, as does the exact make-up of the progenitors. Both leading scenarios of type Ia SNe rely on the formation of a tight binary in which at least one of the companions is a stripped nucleus of an evolved star (that is, a white dwarf224,225). It is the white dwarf that eventually explodes after accreting enough material from its neighbour or merging. The principal difference in the explosion theories then lies with the second object in the binary. If the donor of the fuel for the explosion is a normal non-degenerate star, it is postulated to fill its Roche lobe and transfer its (usually) H-rich gas to the companion until the accreting white dwarf reaches the Chandrasekhar limit of $\approx 1.4 M_\odot$ and explodes224 (though non-degenerate stars might be able to donate He to trigger a type Ia SN, see ref. 225). On the other hand, the donor object could be a white dwarf itself. Then, relatively small amounts of accreted He are required to detonate the explosion in the white dwarf core, thus resulting in the total progenitor mass ranging from sub-Solar to approximately Chandrasekhar (see, for example, refs. 228–232). Differences in the central densities of the progenitors lead to noticeable variation in the rate of production of heavy elements. Mn and Ni in particular (but also Cr and C) are sensitive tracers of the type Ia SN progenitor mass233.

In local ETDs, it is possible to unpick the contributions of type II and type Ia SNe to the chemical composition of the ISM in its early state. The comparison of the abundances of individual light elements against those in the Fe-peak group can provide tight constraints on the yields of type Ia SNe and thus shed light on the nature of their progenitors. In some extraordinary cases, the analysis can be carried out for a single star. Ref. 234 demonstrated that a relatively metal-rich star in the Ursa Major dSph exhibits low $\alpha/\mathrm{Fe}$ ratio as probed by Mg, Si, Ca and Ti, indicative of a prominent type Ia contribution, while simultaneously possessing only traces of Sc, Mn, Cu, V, Ni and Zn. Comparing their measurements with theoretical yield predictions, they argued that such a drastic underproduction of the Fe-peak group elements can only be explained if this star was born from the gas enriched by a sub-Chandrasekhar SN234. Phenomenological descriptions of chemical evolution have been developed to explain the behaviour of several elements with increasing metallicity for a number of dSphs235,236. Although sub-Chandrasekhar explosions must have dominated the enrichment of Sculptor, the more metal-rich systems, such as the Fornax and Leo I dSphs, have SN progenitors with near-Chandrasekhar masses.

This is in agreement with the conclusions of ref. 96, which employed multi-source models similar to those described in ref. 96 and ref. 96 to study the chemical enrichment histories of several massive dwarfs including the LMC, the SMC, Sculptor, Sgr and the Gaia Sausage progenitor, as well as the Milky Way bulge. Compared with the most recent models of double-degenerate SN explosions (such as those in refs. 230,231), ref. 96 concluded that sub-Chandrasekhar SNe have contributed considerably in all systems studied. Depending on the model considered, it is likely that at low metallicities sub-Chandrasekhar SNe are responsible for between 60% and 100% of all type Ia explosions, at intermediate metallicities the variations in the $\mathrm{[Mn/Fe]}$ yield could be a sign of changing progenitor mass and at higher $\mathrm{[Fe/H]}$ the Chandrasekhar channel may become more important.

**The nature of the r-process sites.** Neutron-capture abundances of stars at low and intermediate metallicities in ETDs offer a powerful means of pinning down the astrophysical sites of the r-process enrichment. Of the neutron-capture elements between Ga and U, the best constraints are available for Sr, Y, Zr, Ba and Eu2. Although the s-process contribution is notable in the synthesis of the first four elements, particularly at $\mathrm{[Fe/H]} > -2$, the r-process dominates the production of Eu, even at high metallicities237. Probing the relative contributions of the s- and r-processes is complicated by the fact that the weak Eu absorption lines have only been accessible to high-resolution spectroscopy of bright stars in nearby dSphs238,239,240.

Until recently, it seemed that the heavy-element abundances of stars in dSphs differ considerably from those in the UFDs, making the scarcity of elements such as Sr, Ba and Eu the defining characteristic of the faintest galaxies241,249. This picture was overhauled with the discovery of r-process-enhanced stars in an unassuming UFD, Reticulum 2240,251. Rather than being characterized exclusively by low(er) neutron-capture enrichment at low $\mathrm{[Fe/H]}$, the UFDs display extreme scatter in r-process abundances. Subsequently, several other ETDs have been shown to contain stars enriched in heavy elements. For example, moderate r-process enrichment is reported in another UFD, Tuc 3252. Ref. 253 discovered several stars in the Fornax dSph with extreme Eu enrichment. They associated the birth of these objects with a recent burst of SF activity some 4 Gyr ago246,275. Although not at the same extreme level, ample r-process enhancement has now been registered in the metal-poor stars in the three most massive satellites: the LMC, the SMC232 and the Gaia Sausage254,255.

One way of constraining the nature of the r-process events is through timescales. The abundance ratio of Eu to a reference element produced mostly in CCSNe, for example Mg, compares the r-process delay times to those of exploding massive stars. Ref. 257 examined the $\mathrm{[Eu/Mg]}$ ratios for the classical dSphs and UFDs, as well as the Milky Way halo and disk. The scatter blows up in the metal-poor regime below $\mathrm{[Fe/H]} = -2$, sampled mostly by the UFDs and the Milky Way halo. The most natural explanation for the dramatic spread in the distribution of heavy elements in UFDs is the
stochasticity of their chemical evolution, where the bulk of the ISM pollution is contributed by a small number of events, perhaps even none or just one\textsuperscript{256,257}. The large variation in the heavy-element enrichment and the presence of r-process-enhanced stars in UFDs have been scrutinized with theoretical models. Factors such as (1) the dilution of the enriched gas as it propagates through the dwarf’s ISM after the explosion, (2) the off-centre location of the explosion (due to, for example, a neutron star kick at birth) and (3) the promptness of the SF episode after the explosion may all play a role\textsuperscript{258–261}. Although the number of stars with well-constrained r-process abundances per UFD is minuscule, the larger dSphs offer a more comprehensive picture. Some distinct patterns are noticeable in the plane of [Eu/Mg] versus [Fe/H] at metallicities above [Fe/H] = −2, as shown in Fig. 3. For example, in Carina, [Eu/Mg] is decreasing with increasing [Fe/H], while in Ursa Minor it is growing. In Sculptor and Fornax, [Eu/Mg] shows no trend with metallicity, similar to the Milky Way, but at different levels of the abundance ratio. [Eu/Mg] in the SMC and LMC stays reasonably high (see ref. \textsuperscript{258}). In view of such variety, two independent r-process sites have been suggested, one with a short and one with a long delay time, corresponding to the CCSN and neutron star mergers respectively. This is consistent with the SF and enrichment histories in the Sculptor, Fornax and Sagittarius dSphs\textsuperscript{259,260}, as well as the Milky Way\textsuperscript{261}.

The flatness of the [Eu/Mg] ratio with metallicity in Sculptor may imply synchronization between the r-process events and the CCSN explosions, and thus relatively short delay times for the former. This may disfavour neutron stars as the dominant site if their delay times are of the order of billions of years. However, other interpretations of Sculptor’s flat [Eu/Mg] chemical evolution have suggested that a single population of delayed sources alone may be sufficient\textsuperscript{258,261}. Note that the elevated [Eu/Mg] in the SMC and LMC around [Fe/H] ≈ −2 is unusual, as other dwarfs such as Draco, Ursa Minor and Sculptor all show lower values. Ref. \textsuperscript{258} argued that the peculiar combination of [Mg/Fe] and [Eu/Mg] abundances is a sign of an extended low-level SF from poorly enriched gas in a remote corner of the local Universe.

Conclusions and outlook

There is a continuity of structural and kinematical properties of dwarf galaxies with increasing stellar mass from UFDs through dSphs to the gas-rich LTDs. SF in the UFDs shut down early (\(z \lesssim 3\)), continues with low-level recent activity in the brighter dSphs and remains vigorous in the LTDs today. The lowest-metallicity stars in the ETDs are invaluable tracers of SF in very remote epochs, while detailed chemical abundance patterns offer clues to the nucleosynthetic history of these ancient objects. This Review has stressed the variety of SFHs and chemical-evolution histories sampled by the Milky Way’s ETDs. It is precisely this diversity—once mapped out by a slew of accurate chemical abundances—that will allow us to disentangle the contributions of multiple enrichment sources, simultaneously constraining the dwarfs’ SFHs and the nucleosynthetic yields and thus elucidating the physics of binary evolution and SNe explosions. This inference (see refs. \textsuperscript{98,179} for examples) requires large, accurate and homogeneous samples of chemical abundance measurements, highlighting the role of wide-area high-multiplex surveys such as the ongoing GALAH\textsuperscript{265} and APOGEE\textsuperscript{266} surveys, as well as the upcoming WEAVE\textsuperscript{267}, DESI\textsuperscript{268} and 4MOST\textsuperscript{269} campaigns. The heavy-element production sites are also the points of feedback energy injection into the galaxy’s ISM, capable of reshaping the dwarf’s global morphology. However, only in the Milky Way can the effects of the internal processes be decoupled from the actions of the environment, as the satellites’ orbits are pinned down by Gaia’s astrometry.

The past decade has seen substantial progress, but a number of open questions remain. First, the central parts of many ETDs are believed to be cored\textsuperscript{155,156} with bursty SF or outflows triggered by CCSNe responsible for transforming dark-matter cusps into cores\textsuperscript{258–261}. Although demonstrated as feasible in simulations, particularly for the higher-mass ETDs\textsuperscript{85}, observational confirmation of this ancient process—a cornerstone of our theories of low-mass galaxy formation—is lacking. However, evidence may be sought in the detection of ejected stellar material around ETDs. Wide-area halo mapping with surveys such as the Legacy Survey of Space and Time (LSST) could be used to search for these faint substructures of early stars. The study of low-surface-brightness outskirts is increasingly possible due to Gaia and narrow-band imaging. One recent example is ref. \textsuperscript{271}, which found stars out to \(\sim 7\) half-light radii in Tucana III. Note, however, that dwarf galaxies are capable of assembling extended stellar haloes around themselves via mergers with other dwarfs (see for example ref. \textsuperscript{272}).

Second, the most-metal-impoverished stars are built from the products ejected by the first massive stars (Population III) that polluted the early Milky Way. Direct observation at high \(z\) of individual Population III stars is infeasible. So, the EMP stars—together with their even poorer siblings, the ultra-metal-poor stars with [Fe/H] < −4—are one of the few viable probes. Numbers of EMPs and especially ultra-metal-poor stars are still small, despite the heroic efforts of surveys such as PRISTINE\textsuperscript{267}. However, extensive follow-up of candidates with upcoming spectroscopic surveys such as WEAVE, DESI and 4MOST will soon boost the numbers substantially. Third, the chemical properties of the UFDs remain enigmatic. One avenue that is yet to be fully exploited is high-resolution spectroscopy of the substructures in the Milky Way halo that are the ghosts of ETDs long gone (for example, ref. \textsuperscript{273}). Crucially, these ghosts are much closer than the nearest intact UFDs, which are \(\gtrsim 30\) kpc away. Therefore, such disrupted substructures offer a unique window onto the chemistry of the faintest UFDs. This approach has been followed by ref. \textsuperscript{274} and ref. \textsuperscript{275} for the S2 stream, ref. \textsuperscript{276} for the Orphan Stream and ref. \textsuperscript{277} for the Indus Stream. There is also an urgent need for more high-resolution abundance analyses of stars from intact UFDs, particularly for those at the metal-poor end of their metallicity distributions, to understand the chemical evolution and early star-forming environments of the very faintest ETDs.

This Review has focused on the ETDs of the Milky Way. These may be atypical in some respects, given the quiet accretion history of the Milky Way. Studies of the SF and chemistry of the ETDs around M31 are already ongoing\textsuperscript{279}, while deep HST imaging has uncovered UFDs beyond the Local Group\textsuperscript{280}. The LSST is predicted to increase the number of nearby ETDs by hundreds\textsuperscript{281}. It will also be sensitive to ETDs brighter than \(M_V = −6\) in galaxy groups within 3 Mpc (ref. \textsuperscript{282}). The LSST will certainly tell us whether there is a large population of ETDs still fainter than the UFDs (that is, below the line marking 30 magarcsec\textsuperscript{−2} in Fig. 1), or if there is a surface brightness threshold below which galaxies cannot form. Complementary to local studies, next-generation facilities such as the James Webb Space Telescope may allow us to detect high-\(z\) analogues of the brightest of the Local Group ETDs, assuming that their stars formed early\textsuperscript{88}. The SF and enrichment histories of many more ETDs will become accessible over the next few years with the advent of extremely large telescopes with multi-object \(R = 5,000–30,000\) spectroscopy (where \(R\) is the spectral resolution or resolving power)\textsuperscript{283}. High-resolution spectroscopy is limited to targets within the Milky Way’s virial radius and possibly M31, but medium-resolution spectroscopy will extend to beyond the Local Group. Current facilities limit precise chemical abundances to resolved stellar populations within the Local Group. We can look forward to moving out to megaparsec distances over the next few decades, giving us opportunities to study the detailed enrichment histories of the ETDs in environments that are different from the Local Group.

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The authors declare no competing interests.

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