Observational constraints on stellar feedback in dwarf galaxies

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Feedback to the interstellar medium from ionizing radiation, stellar winds and supernovae is central to regulating star formation in galaxies. Owing to their low mass (<10^5 solar masses), dwarf galaxies are particularly susceptible to such processes, making them ideal sites for studying the detailed physics of feedback. In this Perspective, we summarize the latest observational evidence for feedback from star-forming regions and how this feedback drives the formation of ‘superbubbles’ and galaxy-wide winds. We discuss the important role of external ionizing radiation—reionization—for the smallest galaxies, and the observational evidence that this feedback directly impacts galaxy properties such as their star formation histories, metal contents, colours, sizes, morphologies and even their inner dark matter densities. We conclude with a look to the future, summarizing the key questions that remain to be answered and listing some of the outstanding challenges for galaxy formation theories.

Stars are known to directly impact their surrounding interstellar medium (ISM) through the emission of ionizing radiation, stellar winds and, at the end of the lives of the most massive stars, through supernova explosions. Similarly, central supermassive black holes can also influence their host galaxies through radiation, winds and jets emitted from their surrounding gaseous accretion disks (known as active galactic nuclei; AGN). Finally, ionizing photons from the first stars and galaxies in the Universe can impact the smallest galaxies, inhibiting or shutting down star formation. Collectively, these processes are referred to as feedback. Such feedback is usually assumed to be negative because most of these processes are self-limiting. For example, stellar feedback and external ionizing radiation typically heat the ISM, reducing further star formation, whereas AGN feedback shuts off the flow of cold gas to the supermassive black holes, preventing further feedback. However, positive feedback is also possible, for example when stellar winds compress the surrounding ISM, or when a galaxy-wide wind impacts a hot surrounding corona, triggering gas cooling and further star formation. Nonetheless, negative feedback must dominate over positive feedback, at least when averaged over the scale and lifetime of galaxies. Otherwise, star formation would be far more efficient than is observed. Averaged over the whole Universe, galaxies convert only ~6% of the available hydrogen into stars, with Milky Way-mass galaxies (of stellar mass M_☉ ≈ 10^11 solar masses (M_☉)) being the most efficient and dwarfs (M_☉ < 10^8 M_☉) the least efficient. This decreasing star formation efficiency with decreasing galaxy mass hints at the important role of stellar feedback in regulating galaxy growth.

The importance of stellar feedback for sculpting the properties of galaxies has been well established for over 50 years. Motivated by the lack of ISM in massive ellipticals, early work posited that galactic-scale winds driven by supernovae could explain the absence of ionized and neutral hydrogen observed in these systems. Subsequent works extended this to explain the properties of dwarf galaxies, where feedback could not only account for a lack of ISM, but also the low metal yields and diffuse nature of these systems. As models and simulations have improved, it is clear that supernovae and stellar feedback have a substantial impact on not only the luminous properties of the smallest galaxies, but also their dark matter haloes. Indeed, there is mounting dynamical evidence for this in dwarf galaxies at both low and high redshift. Finally, the very smallest galaxies (M_☉ < 10^9 M_☉), ionizing radiation from the first stars and galaxies in the early Universe (at z ≳ 8–12) heats their ISM, shutting off further accretion of cold gas. Starved of fresh fuel for star formation, these galaxies then cease to form stars after z ≈ 4, leaving behind ‘ultrafaint’ dwarfs with only old-age stellar populations. We will refer to the cessation of star formation—by any mechanism—as quenching.

In this Perspective, we present direct observational evidence for negative stellar feedback in dwarf galaxies, which are defined here as galaxies with M_☉ < 10^9 M_☉. We first show how stellar feedback acting on 10–100 pc scales in individual star-forming regions leads to the formation of superbubbles and galaxy-wide winds. We then discuss the impact of stellar feedback on the star formation histories (SFHs), sizes, colours, metal contents and inner dark matter densities of dwarfs, providing further indirect evidence of feedback, while simultaneously highlighting its important role as a key regulator of galaxy formation and evolution. Finally, we look to the future and discuss key unanswered questions.

Direct evidence for stellar feedback in dwarf galaxies

From star-forming regions to superbubbles to galactic winds. Galactic winds are galaxy-scale gas outflows composed primarily of hydrogen, but also containing heavier elements and even molecules (see the ‘Dwarf galaxy winds’ section). They are produced by one of two mechanisms: AGN feedback, which is the subject of a related Perspective, and stellar feedback, which is the focus of this Perspective. In this section, we combine observations of star-forming regions, the ISM and the circumgalactic medium (CGM) of dwarf galaxies to show how stellar feedback drives the formation of superbubbles and galaxy-wide winds (Fig. 1).

Stellar feedback begins on 10–100 pc scales inside young star clusters. There, massive stars deposit energy and momentum into the ISM via photoionizing feedback and associated radiation pressure, stellar winds, cosmic rays, and supernovae, with additional sources of feedback from binary stars. Observations of nearby star-forming regions demonstrate that radiative feedback and winds act to ‘preprocess’ the surrounding birth gas cloud, ionizing
the surrounding gas to create expanding H ii regions\(^27\). After a few million years, the most massive O, A and B stars explode as type II supernovae\(^30,32\). The correlated supernova energy from multiple young stars impacts the surrounding preprocessed ISM to drive a hot, expanding bubble of X-ray-emitting and ionized gas\(^31,33\) \(\text{(Fig. 1b). As multiple bubbles break out from their natal birth clouds, they expand to sizes >100 pc and overlap to form superbubbles.}

Several such superbubbles have been observed in exquisite detail in the nearby Large Magellanic Cloud (LMC, ref.\(^4\); see also Fig. 1a(i)). The largest of these require hundreds to thousands of supernova explosions to power them\(^5,39\), although other forms of feedback such as stellar winds and radiation pressure also contribute to the energy budget, especially at early times before supernovae explode\(^4\). Note that the terms bubble and superbubble are sometimes interchangeably in the literature, and 'shell' can refer to the boundary of a bubble, a superbubble or even a larger-scale galactic wind. To avoid confusion, we define 'bubble' here as an expanding shell of interstellar material surrounding hot, X-ray-emitting gas that is <100 pc in diameter. A superbubble is then a bubble that is >100 pc diameter\(^4\).

We call the shell of the (super)bubble the (super)bubble shell, and refer to the boundary between a galaxy-wide wind and the ISM/CGM as the wind shell.

The inverse of superbubbles are H i holes—evacuated regions in the colder H i gas of dwarf galaxies inside which superbubbles typically expand\(^4,37\). The origin of such holes has been debated historically, with theories ranging from gravitational instability\(^38\) to gamma-ray bursts and the impact of high-velocity clouds\(^39\). However, modern data have uncovered a tight correlation between the smaller, faster expanding H i holes and OB associations (the sites of massive star formation\(^4,31,32\); Fig. 2). This, combined with the fact that the energy required to produce the observed expansion velocity of H i holes (typically \(<10–20 \text{ km s}^{-1}\)) is consistent with the expected supernova energy input from these OB associations\(^39\), suggests that stellar feedback is primarily responsible for H i holes in dwarf galaxies. We show an example of H i holes and their correlation with OB associations for the nearby dwarf irregular galaxy IC1613 in Fig. 2a. Note that the smallest, fastest-expanding holes correlate well with OB associations (blue), whereas the largest H i holes have no measured expansion and correlate poorly with the OB associations. Assuming an initial expansion velocity of \(v_i = 20 \text{ km s}^{-1}\) (typical for the smallest holes)\(^4\), an initial hole diameter of \(r_i = 100 \text{ pc}\), a final diameter of \(r_f = 1 \text{ kpc}\) and that the hole expansion velocity \(v_f\) linearly falls to zero as the hole reaches its maximum size, an H i hole will reach its maximum diameter in \(t_f = (r_f - r_i)/v_i \approx 88 \text{ Myr}\). For a typical dwarf irregular galaxy, this is approximately half of the local dynamical time (Fig. 3b). As such, we expect that any correlation between local star formation and H i holes will be rapidly erased as the hole expands, the young stars die and any remaining stars begin to phase mix in the disk.

As superbubbles continue to grow, they can overlap to form galaxy-wide winds (Fig. 1a(ii)). These winds carry gas from the star-forming disk to the CGM, if sufficiently energetic (Fig. 1a(iii); see also ref.\(^4\)). By measuring the dynamical ages and expansion times of winds and comparing them to the recent star formation activity of the galaxy, we can show that the winds are consistent with being launched by starburst activity. For example, H\(\alpha\) imaging and spectroscopy were used to determine\(^4\) a dynamical age of \(\leq 25 \text{ Myr}\) for the galactic outflow in NGC 1569, consistent with recent star formation activity. A number of other studies find similar timescales\(^35,44\).

**Dwarf galaxy winds.** The presence of large-scale gaseous outflows has long been inferred from observations of dwarf galaxies; one exceptional example is the majestic M82 system\(^4\) (Fig. 1), the only dwarf galaxy in the local Universe that exhibits a developed and powerful wind. Although something of an outlier, M82 helps to demonstrate the possible characteristics of an extreme wind. Galactic winds are cone-like in shape, moving at velocities of 25–100 km s\(^{-1}\) perpendicular to the galaxy's stellar and gaseous disk\(^35,46,47\). They are also multi-phase, typically containing hot \((T > 10^4 \text{ K})\),
Fig. 2 | H i image and rotation curves of the nearby dwarf irregular galaxy IC1613. a, Isodensity contour map of the H i gas distribution (grey shaded contours), showing both large H i holes that are not expanding and smaller holes (inset) that are rapidly expanding. The open blue circles show star-forming regions (OB associations). Note that the locations of the OB associations correlate well with the smaller, rapidly expanding holes, consistent with the holes being a result of stellar feedback. Data from refs. 34-36. b, Rotation curves for IC1613 derived from its H i gas kinematics (assuming inclinations (i) of 39° or 20°)39. The blue square shows the circular speed at the half-light radius, derived from the stellar kinematics of IC161345. In all cases, the error bars mark the 68% confidence intervals. The horizontal grey band marks the expected peak circular speed if IC1613 were to lie along the baryonic Tully–Fisher relation (BTFR)—a tight empirical relation between the peak rotation speed of dwarfs and their total baryonic mass144,145. The locations of the largest H i holes in a are marked by the black horizontal lines. Note that the H i holes coincide with prominent ‘dips’ in the rotation curves, while the expansion velocity of the smallest H i holes (inset in a) is comparable to the rotation speed in the inner regions. The presence of these holes makes it especially challenging to correct for inclination in this galaxy and derive its true circular speed curve39. Standard techniques favour i = 39 ± 2° and a very low inner rotation speed (black data points). However, this is inconsistent with the circular speed derived from IC1613’s stellar kinematics (blue square). This suggests that IC1613’s true inclination is closer to i = 20° (grey data points), meaning that it is no longer an outlier from the BTFR.

Fig. 3 | Latest observational constraints on bursty star formation in dwarf galaxies. a, The SFR density fraction of dwarf galaxies in the Sloan Digital Sky Survey with continuous versus bursty star formation. b, Constraints on the burst timescale (r in equation (1)) as a function of stellar mass. The green circles show data from ref. 94; the horizontal error bars mark the bin size and the vertical error bars mark the formal 68% uncertainties. The blue star shows the expected range of dynamical times at the half-light radius, R1/2, for dwarf irregular galaxies in a Λ cold dark matter (ΛCDM, where Λ is the cosmological constant) cosmology (see the text for details of how this is calculated). Bursts below this band will drive a damaging, impulsive response on their host galaxy stars and dark matter; bursts above this line yield a more gentle, adiabatic response. c, Constraints on the maximum amplitude of star formation bursts (A in equation (1)) as a function of stellar mass. The legend in b also applies to c.

warm (10^3 < T < 10^4 K) and cold (T < 10^3 K) components that entrain metals, molecules and dust47,48. Despite M82 presenting us with a very obvious detection of winds, identifying and categorizing winds in dwarf galaxies is observationally challenging. The winds are diffuse, and the irregular morphologies and kinematics make the characterization of winds difficult. For the nearest systems, clear Hα shells and bubbles can be identified49; but further afield, classifying and characterizing these winds is more subjective (see ref. 49 for a discussion). Hard X-ray observations constrain the hottest phase of the wind (T > 10^6 K), and are usually concentrated on the star-burst generating the wind as this is where the denser gas is found40,41 (Fig. 1b). Soft X-ray observations probe gas locked in the slightly cooler ~10^6 K phase. This is usually observed at the boundary of the hot and warm phases, and traces (super)bubbles formed from correlated supernova events (see the ’From star-forming regions to superbubbles to galactic winds’ section and and Fig. 1a(iii)).
phase is thought to be the most energetic and most metal-enhanced component. It has the greatest chance of escaping the disk, and even the halo, of the galaxy, enriching the CGM as shown for M82 (ref. 41). The presence of diffuse, soft X-ray emission beyond the H I disk is thus typically interpreted as an outflow event. Unfortunately, owing to the low surface brightness of the emission, X-ray observations (both hard and soft) are typically limited to the most energetic starburst systems (such as M82, NGC 4449, NCG 625, NGC 1569 and NGC 4214) and are likely to fade only ~25 Myr after the starburst that generated them41. As such, we do not expect such a hot wind to be ubiquitous in dwarfs.

The warm phase (T ≈ 10^4 K) is traced with ionized hydrogen using observations in the far UV and optical/Hα (refs. 35,47,59). Most of the mass is entrained in this phase (Fig. 1a(i), (iii)), and so it is crucial to determining the rate of mass outflow (M_dot, the rate of change of mass per unit time) and the mass loading of the winds (see the ‘The wind mass-loading factor’ section). Rest-frame UV absorption lines are commonly used to study outflows in galaxies at high and low z using space-based observatories such as HST-COSMOS ORIGIN Spectrographs and the former Far Ultraviolet Spectroscopic Explorer spacecraft (refs. 35,47,59). In general, UV and Hα studies find that dwarf galaxies with more centrally concentrated star formation are more likely to host a substantial wind47. They also found that the majority of the material in dwarf galaxy winds is not moving fast enough to escape the gravitational potential. Instead, the winds are consistent with moving the majority of the material into the haloes of the dwarfs, where it can be recycled, while a smaller fraction can be transported into the intergalactic medium (IGM).

Finally, the cold phase (T ≈ 10^2 K) is typically traced with H I, H_2 and CO observations (Fig. 1b). The molecular phase is thought to carry a significant mass fraction in outflows51. Cold outflows have been observed in some dwarf systems, including M8255,61,66, where CO and H_2 are associated with the hot outflow, and can be traced to distances of ~3 kpc beyond the mid-plane. The neutral component of winds is expected, and typically observed, to be small. Nonetheless, it is important as a key discriminator of theoretical models, many of which predict purely hot outflows for dwarfs51. It may point, for example, to an important role for cosmic ray feedback. Cosmic rays accelerate gas more gradually and at all temperatures (the cold phase)67,650.

The link between star formation and outflow rates. Winds and outflows are ultimately powered by star formation activity (see the ‘From star-forming regions to superbubbles to galactic winds’ section). Knowing the SFR during a starburst is key to characterizing an observational wind and quantifying the mass loss so it can be compared to theoretical predictions. This is encapsulated in the mass-loading factor, η, which we discuss in the ‘The wind mass-loading factor’ section. This compares M_dot to the instantaneous SFR. As such, a solid understanding of the SFR is essential for understanding the outflow rates of galactic winds.

There are several techniques for determining the SFR. For nearby galaxies where we can resolve individual stars, their stellar populations are used to determine the SFH over periods of hundreds of million years to a Hubble time using the synthetic colour magnitude diagram (CMD) fitting approach51–60. In this process, a Monte Carlo calculation is run to reproduce the features of a CMD using stellar models (isochrones) with different ages, initial mass functions (IMFs), binary fractions, metallicities and other physics to find out which combinations of stellar populations best match the observations44,61,62,71,72. For starbursting dwarfs with resolved bright stars, one can constrain the SFH over the past ~1–2 Gyr well, covering their recent and ongoing starbursts64,67,71. For systems where the stars cannot be resolved, one can infer recent SFRs using Hα or UV observations. As Hα traces O-type stars, the strength of the flux equilibrates on timescales of ~5 Myr during constant star formation. UV observations trace O, A and B stars. As A and B stars are longer lived, the time resolution for these observations is ~100 Myr. As SFRs can exhibit fewfold variation on timescales shorter than 100 Myr, UV observations can be uncertain by a similar factor70.

Fig. 4 | Mass-loading rates as a function of stellar mass from several recent studies of outflows in dwarf galaxies. The data points are colour coded by the sSFR. All are plotted with uncertainties, but some are smaller than the size of the markers. The dashed line shows a theoretical prediction for mass loading taken from the FIRE-1 simulations, which is typically higher than the majority of observations. The solid line shows the same but from the FIRE-2 simulations, which still overpredict the mass loading at the lowest masses. Both are similar to other models (a more detailed comparison can be found in ref. 43). Intriguingly, the recent measure of mass loading from the LMC from deep Hα mapping is consistent with these models.

The wind mass-loading factor. Above, we discussed how Hα and far-UV observations can be used to measure M_dot, and gave an overview of the star formation metrics used to determine the available power provided by the stars. Here, we combine these to determine the strength of galactic winds using η, defined as the ratio between M_dot and rate of star formation that powers the wind (M_SFR, or SFR). Several recent works have reported mass-loading values for dwarf galaxies spanning 10^7 ≤ M ≤ 10^10 M⊙ (refs. 47,55,64,71). These are shown as a function of stellar mass in Fig. 4. These studies also investigated whether η scales with stellar mass, circular velocity (a proxy for total mass), the SFR and the spatial concentration of star formation. There are differences in their findings, but some of these are due to subtleties in observational methods, galaxy samples and modelling assumptions. They also compare their findings to high-resolution simulations with different ‘subgrid’ models for star formation and stellar feedback. We summarize these results here, and discuss their implications.

Given the shallower potential wells of dwarf galaxies, it is typically assumed that η will increase with decreasing mass or luminosity. However, this is not always seen in observations. We show three compilations of data in Fig. 4: UV samples from ref. 51 and ref. 53, and
Hα results from ref. 47. Interestingly, the authors of ref. 53 and ref. 47 found little to no relation between stellar mass (or total mass) and \( \eta \), whereas those of ref. 54 found a reasonably steep relation for their sample of seven systems.

Although these results seem contradictory, there are some nuances. For the two UV samples, different assumptions were used for the outflow density, metallicity and spatial coverage. Ref. 53 assumed a constant density and metallicity across their sample, and set the outflow radius to twice that of the star formation region, whereas ref. 44 included observationally motivated values on a galaxy-by-galaxy basis. The authors found that this led to values of \( \eta \) that differed by a factor of 10 (compare with ref. 53). In ref. 45, they used deep Hα maps for their systems, meaning they were able to directly measure the extent of the winds, an advantage over pencil beam UV surveys that have limited coverage of the wind region.

The way that the SFR is measured also differs between studies. The Hα study used the temporally resolved SFH derived from HST photometry, whereas the UV studies scaled the UV flux. This had the effect of tying the SFR to a 100 Myr timescale (longer than the warm gas cooling time). These also depend on scaling relations that can underpredict the SFR by 50%, compared with those measured empirically from CMDs, leading to values for mass loading that are 50% higher.

The properties of the sample galaxies also differ. In Fig. 4, we colour code each point by its specific SFR (sSFR) to show how extreme the current star formation is in each system. In general, the UV studies include more extreme starbursts than the Hα study, which could lead to different biases for both methods. All three studies found that it is not only the amount of star formation in these systems that matters, but its spatial distribution. Systems with strongly concentrated starbursts show higher mass-loss rates than those with more extended star formation.

Comparing relations with total mass (or circular velocity) between observations and simulations can be misleading, as one is not comparing like with like. The circular velocities can be measured at vastly different radii, and the maximum circular velocity is not always observed as the rotation curves are still rising within the extent of the dataset. There are also issues with non-circular motions in H1 gas and measuring precise inclinations for galaxies that can introduce biases (see the ‘ Morphology and size ’ section). Comparing with stellar mass is thus more straightforward. In Fig. 4 we show the mass-loading prediction within the FIRE-1 and FIRE-2 suites of simulations61,76, which increases with decreasing stellar mass. The two versions span the observations, with FIRE-1 typically higher than the majority of observations at all masses, but the difference is particularly striking below \( M_\star < 10^5 M_\odot \). FIRE-2 is closer to the bulk of observations, although it still overpredicts at the lowest masses. This is seen in other large-scale simulations (such as in fig. 10 of ref. 47). So, are cosmological simulations overestimating the amount of mass loss in the lowest-mass galaxies?

Maybe, maybe not. Higher-resolution simulations of individual dwarf galaxies do predict lower mass-loss rates than the cosmological simulations discussed above, more comparable to observations7–79. These show the importance of different modes of stellar feedback, and their impact on mass loading. A further consideration is whether observations are capturing all of the material within winds in low-mass systems. As all authors note, these features are extremely challenging to observe. If there is more material just below the detection threshold of these observations, the mass-loading factors could rise significantly. This has been seen in a new study of the LMC using extremely deep Hα observations across the whole galaxy84. The LMC has a lower sSFR than the starbursting dwarfs presented in most other studies, and so may be assumed to have a lower mass-loading factor. However, in Fig. 4 (where the LMC is shown as a diamond) it is perfectly consistent with the higher FIRE-1 predictions. Although this result is for just one galaxy, and also has a range of assumptions made about the geometry and distribution of the wind, it makes the compelling case that we may not be capturing all the outflowing material in more distant galaxies. Future facilities will allow us to obtain deeper data for more systems to test this.

**The impact of feedback on dwarf galaxies**

**Bursty star formation.** Stellar feedback acts to regulate star formation in dwarfs, lowering their stellar masses significantly compared with a Universe in which no feedback is present52,80. It also impacts the whole baryon cycle and, therefore, how star formation proceeds with time. The latest numerical simulations of dwarf galaxy formation have now reached a resolution and physical fidelity that can resolve the cold, dense ISM with a mass and spatial resolution of better than \( 100–1,000 M_\odot \) and \( \Delta x \approx 10–100 \) pc, gas cooling below \( T\approx 100 \) K and resolved gas densities of \( \rho_g > 100 \) atoms per cubic centimetre (refs. 3,81–83). This is a key milestone as it means that simulations can capture the formation of the most massive molecular clouds, forming stars in the right places at the right times, and thereby have feedback impact the ISM in a more realistic manner than the previous generation of simulations (see the companion Review on simulations of dwarfs85). Such simulations universally predict that star formation in dwarfs should be ‘bursty’, with a duty cycle comparable to the local dynamical time and peak-to-trough variations in the SFR of a factor of ~5–10 (ref. 86). As such, the variability of star formation in dwarfs serves as an indirect probe of feedback and an important test of the latest theoretical models.

In Figure 3, we collate the latest data constraints on the variability of star formation in dwarf galaxies. Such variability is probably driven by a range of physical processes, including stellar feedback, galactic interactions86,87 and galaxy mergers82,88. However, galactic interactions and mergers typically occur on billion-year timescales, much longer than the dwarf starburst cycle82. As such, although variability on roughly billion-year timescales has been reported for nearby dwarfs60,74, we focus here on studies that probe the shortest period bursts, as these are most likely to probe the starburst cycle. The age resolution of SFHs derived for individual galaxies from resolved CDMs is ~1 Gyr, falling to ~200 Myr only for the youngest age stars (see the ‘The link between star formation and outflow rates’ section and refs. 24,64,67,70–73,85). As this is coarser than the burst timescale predicted by the latest simulations, we must take a different approach: studying the statistics of star formation indicators that probe different timescales (see the ‘The link between star formation and outflow rates’ section). The results from these two studies are replotted in Fig. 3. Figure 3a shows the SFR density fraction of dwarfs with continuous star formation (blue) versus those undergoing a burst (red) drawn from the data. The SFR density fraction of dwarfs with continuous star formation (blue) versus those undergoing a burst (red) drawn from the data.
ref. 93. Note that the burst fraction approaches unity as the stellar mass is decreased (recall that we define dwarf galaxies as having \( M < 10^9 M_\odot \)). Figure 3b shows the burst timescale (defined as in equation (1)). Ref. 93 only provided a back-of-the-envelope estimate of the burst timescale for dwarfs with \( M \approx 10^8 M_\odot \) (blue star in Fig. 3b). Nonetheless, this is in excellent agreement with a more recent analysis\(^4\) (green data points). The grey band marks the expected range of dynamical times at the half-light radius, \( R_{1/2} \), for dwarf irregular galaxies in a CDM cosmology. (For this calculation, we used the \( M \sim M_{200} \) (halo mass) relation from ref. 97, and its \( 1 - \sigma \) scatter, to estimate the dark matter halo mass as a function of stellar mass. We then assumed the median halo concentration parameter, \( c_{200} \), from the \( M_{200} - c_{200} \) relation from ref. 94, valid for a CDM cosmology. We estimated \( R_{1/2} \) using the \( R_{1/2} - r_{200} \) (virial radius) relation from ref. 96. And, finally, we assumed that the dynamical mass is dominated by the dark matter halo, which is of Navarro–Frenk–White\(^4\) form.) If the burst timescale is longer than the local dynamical time, then the stars and dark matter in the galaxy will respond adiabatically to any gas mass loss driven by the burst. By contrast, if the burst timescale is shorter than the local dynamical time, this will yield an impulsive response. This is an important distinction because an impulsive response will irreversibly pump energy into the orbits of stars and dark matter particles, lowering the inner dark matter density\(^1\). We will discuss this further in the “The inner dark matter density of dwarfs” section.

Finally, Fig. 3c shows observational constraints on A (defined as in equation (1)), from ref. 94 (green data points). As in Fig. 3b, an estimate from ref. 94 is marked by a blue star. Note the good agreement between ref. 93 and ref. 94 despite the fact that these studies used very different data and methodologies, and that the burst amplitude increases dramatically as \( M \) falls.

The above data demonstrate that star formation in dwarf galaxies is indeed bursty. However, it is important to note that the precise burst frequency, amplitude and duration may be impacted by systematic errors. First, near the flux-limit, surveys will be biased towards starbursting dwarfs because they are more luminous\(^8\). Second, the combination of UV continuum and hydrogen recombination lines is an imperfect measure of starbursts\(^1\).\(^2\).\(^3\).\(^4\). Third, simple ‘exponential’ burst models, or similar, may produce biased inferences when applied to real SFHs\(^4\).\(^5\).\(^6\).\(^7\).\(^8\). Mock data drawn from the FIRE-2 simulations suggests that only the first of these three is a significant concern\(^8\).\(^9\).\(^10\). Detailed comparisons between these same simulations and the data from ref. 93 (Fig. 3c) shows good agreement in the burst properties of low-mass dwarfs, but above \( M > 10^8 M_\odot \), the simulated burst timescale is too short (<30 Myr). The reasons for this discrepancy remain to be understood, but could plausibly be a result of missing ’sub-grid’ physics and/or resolution effects\(^8\).\(^9\).\(^10\).\(^11\).

Quenching. Although star-forming dwarf irregular galaxies show a continuous cycle of star formation bursts, dwarf spheroidal galaxies show no recent star formation and no detectable H\(_\alpha\) gas\(^1\).\(^2\).\(^3\).\(^4\). This quenching could be another hallmark of the impact of stellar feedback. However, dwarf spheroidals are typically found close to a larger host galaxy, whereas star-forming irregulars are more isolated\(^7\).\(^8\).\(^9\).\(^10\).\(^11\). Indeed, ref. 109 showed that essentially no dwarf galaxies—under our definition of a dwarf—are quenched, if sufficiently isolated. This suggests that most dwarfs are primarily quenched by environmental effects, although these are probably enhanced by stellar feedback\(^1\).\(^2\).\(^3\).\(^4\).\(^5\).\(^6\). For more massive dwarfs, the most likely environmental mechanism is ‘ram-pressure’ stripping of their ISM when they fall into a larger host galaxy\(^1\); for the very smallest ultrafaint dwarfs (\( M \lesssim 10^7 M_\odot \)), the most likely mechanism is reionization: ionizing photons from external galaxies and quasars in the redshift range \( z \approx 6–10 \) (ref. 115). Evidence for this latter comes primarily from ultrafaint dwarf galaxy SFHs, as measured from deep CMD. Ref. 24 included a study of six nearby ultrafaint dwarfs, all of which have extremely similar stellar populations, with close to 100% of their stars formed by \( z \approx 4 \). This is consistent with the latest models of reionization quenching, in which self-shielding of dense gas allows some star formation to proceed even after reionization has completed\(^8\).\(^9\).\(^10\).\(^11\).\(^12\). Further evidence for this comes from the dynamical masses of ultrafaint dwarfs. Estimates from both their stellar kinematics and abundance matching place ultrafaint dwarfs in haloes of mass \( M_{200} \approx 10^8 M_\odot \) (ref. 93), consistent with the latest models of reionization quenching\(^1\).\(^2\).\(^3\).\(^4\).\(^5\).\(^6\).\(^7\).\(^8\).\(^9\).\(^10\).\(^11\).\(^12\).

Despite the important role of environment quenching, it is possible that some dwarf spheroidals are quenched by their own internal stellar feedback alone\(^1\).\(^2\).\(^3\).\(^4\).\(^5\).\(^6\). Such dwarfs should have more extended star formation than the ultrafaints and yet be as isolated as the star-forming dwarf irregulars. An unambiguous candidate has yet to be found\(^7\).\(^8\), but may be discovered in upcoming surveys such as that planned at the Vera Rubin Observatory.

The suppression and quenching of star formation in dwarf galaxies is key to solving a long-standing tension between the number of observed galaxies orbiting the Milky Way and M31 and the large numbers of bound dark matter haloes predicted in \( \Lambda \) CDM structure-formation simulations—the ‘missing satellites problem’\(^1\).\(^2\).\(^3\).\(^4\).\(^5\).\(^6\).\(^7\).\(^8\).\(^9\).\(^10\).\(^11\).\(^12\).\(^13\). The scale of this problem has reduced with time, as newer predictions have revised the expected number of satellites downwards and new surveys have found ever larger numbers of nearby ultrafaint dwarfs\(^7\).\(^8\).\(^9\).\(^10\).\(^11\).\(^12\).\(^13\).\(^14\).\(^15\).\(^16\). The latest observations of isolated dwarf irregulars demonstrate that star formation becomes increasingly inefficient as the halo mass is reduced, almost certainly due to stellar feedback\(^7\).\(^8\).\(^9\).\(^10\).\(^11\).\(^12\).\(^13\).\(^14\).\(^15\).\(^16\).\(^17\).\(^18\).\(^19\).\(^20\). This solves the missing satellites problem, at least down to the mass scale of ultrafaint dwarfs, by rendering the lowest-mass dark matter haloes too faint to be observed, or even fully dark\(^7\).\(^8\).\(^9\).\(^10\).\(^11\).\(^12\).\(^13\).\(^14\).\(^15\).\(^16\).\(^17\).\(^18\).\(^19\).\(^20\).\(^21\).\(^22\).\(^23\).\(^24\). Note that isolated dwarf irregulars are a better test bed for studying feedback processes than satellite dwarf galaxies. This is because satellites can lose significant gas, stellar and dark matter mass and/or have their star formation enhanced or shut down via environmental processes\(^7\).\(^8\).\(^9\).\(^10\).\(^11\).\(^12\).\(^13\).\(^14\).\(^15\).\(^16\).\(^17\).\(^18\).\(^19\).\(^20\).\(^21\).\(^22\).\(^23\).\(^24\). This makes it much harder to determine which aspects of their observed properties today are attributable to stellar feedback alone.

Morphology and size. If bursty star formation drives repeated outflows on a timescale comparable to, or shorter than, the local dynamical time, this will drive an irreversible, impulsive energy injection into the stars, dark matter and gas in the host dwarf\(^7\).\(^8\).\(^9\).\(^10\).\(^11\).\(^12\).\(^13\).\(^14\).\(^15\).\(^16\). As shown in Fig. 3b, current observational constraints on star formation in dwarfs suggest that this is indeed the case. If so, then stellar feedback should also impact the size and morphology of dwarf galaxies. There are several lines of observational evidence for this, albeit all indirect. First, nearby dwarf irregulars are observed to show a radial gradient in their stellar ages, with older stars lying farther out and younger stars being more centrally concentrated\(^7\).\(^8\). Ref. 128 showed that this is expected if star formation proceeds in repeated impulsive bursts, driving gas outflows that cause stars to slowly migrate outwards. Second, the same process drives size fluctuations that are consistent with current observational constraints\(^7\).\(^8\). Third, it can explain the existence of ‘ultra-diffuse’ low-surface-brightness dwarfs (defined as galaxies with large effective radii, over 1.5 kpc, and low central surface brightnesses, equivalent to less than \( \mu_V \approx 23.5 \) in the V band; ref. 190,191,192,193,194, although we note that this formation pathway is not without its problems\(^1\).\(^2\).\(^3\).\(^4\).\(^5\).\(^6\).\(^7\).\(^8\).\(^9\).\(^10\).\(^11\).\(^12\).\(^13\).\(^14\).\(^15\).\(^16\).\(^17\).\(^18\).\(^19\).\(^20\).\(^21\).\(^22\).\(^23\).\(^24\). and is just one among several proposed mechanisms\(^1\).\(^2\).\(^3\).\(^4\).\(^5\).\(^6\). Fourth, it yields kinematically hotter stellar populations\(^4\), similar to those observed in nearby dwarf irregulars\(^7\).\(^8\).\(^9\).\(^10\).

Stellar feedback can also cause fluctuations in the gas rotation velocity that hamper our ability to accurately model the masses of dwarfs. Here, there are two main effects. First, numerical models predict that the gas rotation speed should physically fluctuate, rising more steeply during a starburst and less steeply during quiescent
The inner dark matter density of dwarfs. In the previous section we argued that repeated impulsive gas blow-out will pump energy into the orbits of stars, causing dwarf galaxies to slowly expand and puff up vertically. The same physics is also expected to act on the dark matter particle orbits, an effect that has become known as dark matter heating\(^\text{(20,157,202)}\). This is of particular importance, as it can solve two further small-scale tensions in the ΛCDM model. The first is the ‘cusp–core’ problem: pure dark matter structure-formation simulations in the ΛCDM model predict high-density central dark matter cusps in dwarf galaxies, whereas observations have long favoured shallower, lower-density cores\(^\text{(19,47,148)}\). Dark matter heating alleviates this tension by slowly pushing dark matter out from the centres of star-forming dwarfs, transforming the cusp to a core\(^\text{(19,202)}\). The second tension is the ‘too big to fail’ problem\(^\text{(19,149,159)}\); the inner densities of massive satellite dwarfs are also lower than expected from pure dark matter structure-formation simulations in the ΛCDM model. When coupled with the fact that tides have a stronger effect on lower-density dwarfs, too big to fail can be recast as the cusp–core problem but applied to satellites\(^\text{(7,183,184)}\). As such, dark matter heating naturally alleviates too big to fail as well\(^\text{(19,159)}\). (Note that dark matter heating may be further amplified in dwarf galaxies that host an AGN, if feedback from the AGN drives additional, impulsive gravitational potential fluctuations\(^\text{(185)}\). It remains to be seen whether such effects are required in addition to stellar feedback to explain the observed properties of dwarfs).

There is mounting observational evidence from the kinematics of stars and gas in dwarf galaxies that their inner dark matter haloes do indeed puff up in response to stellar feedback. A key prediction of dark matter heating models is that complete core formation must take many dynamical times (since each starburst cycle takes approximately a dynamical time (Fig. 3), whereas each cycle couples supernova energy very inefficiently to the dark matter particle orbits\(^\text{(19,157,202)}\). As such, many cycles are required to sufficiently lower the inner dark matter density to a flat, constant-density dark matter core\(^\text{(20)}\). This means that, all other things being equal, dwarf galaxies with little star formation should have steeper central dark matter cusps than those with more star formation. Ref. \(^\text{154}\) parameterized this using the ratio of stellar-to-dark matter halo mass, \(M_*/M_{\text{200}}\) predicting that galaxies should be cuspy for \(M_*/M_{\text{200}} \leq 5 \times 10^{-4}\) and maximally cored for \(M_*/M_{\text{200}} \approx 5 \times 10^{-3}\).

Ref. \(^\text{21}\) measured the inner dark matter densities of 16 nearby dwarf galaxies with high-quality data and a range of SFHs to test this prediction. They found an anticorrelation between the inner dark matter density (measured at 150 pc) and \(M_*/M_{\text{200}}\), with the approximate transition from cuspy to cored systems occurring at \(M_*/M_{\text{200}} \approx 5 \times 10^{-4}\), exactly as predicted by ref. \(^\text{154}\). These results have been corroborated and expanded upon by ref. \(^\text{21}\). Their data overlap with ref. \(^\text{154}\) at \(M_*/M_{\text{200}} \approx 5 \times 10^{-4}\), but extend to higher \(M_*/M_{\text{200}}\) showing the increasing inefficiency of dark matter heating as \(M_*/M_{\text{200}}\) rises above \(10^{-3}\), again as predicted by ref. \(^\text{154}\).

The above observational constraints bring us to the remarkable conclusion that stellar feedback not only regulates star formation in dwarf galaxies, but actively reshapes their inner mass distributions. This implies that, whatever dark matter is, it is dynamical—it can be moved around by a fluctuating gravitational field. This is suggestive of models in which dark matter is a new, weakly interacting particle. But the nature of this particle is unknown, and a wide range of models remain consistent with the data for the time being\(^\text{(135–139)}\).

The stellar mass–metallicity relation. Stellar feedback also regulates the chemistry of dwarf galaxies. Numerical models suggest that metals are more efficiently ejected by winds into the CGM\(^\text{(160–162)}\), which is supported by the tentative observation of a metal-rich CGM around the isolated dwarf irregular WLM\(^\text{42}\). Indeed, ref. \(^\text{85}\) argued that the stellar mass (or absolute magnitude, \(M_*)\)—metallicity relation \((\text{[Fe/H]}-M_*)\) is the only observable, global scaling relation for nearby dwarfs that is sensitive to feedback physics.

Figure 5 shows the observed [Fe/H]–\(M_*) relation for the Milky Way (purple circles; ref. \(^\text{100}\) and S. Y. Kim et al., manuscript in preparation), isolated Local Group dwarfs (orange stars, ref. \(^\text{100}\)), M31 (cyan pentagons, ref. \(^\text{163–166}\); Kim et al. manuscript in preparation); FIRE \(^\text{170}\); and Justice League\(^\text{171}\). Ref. \(^\text{85}\) showed that the [Fe/H]–\(M_*) relation is consistent with current data. Stronger feedback ejects more metals per unit stellar mass causing the galaxy to fall significantly below the [Fe/H]–\(M_*) relation. Conversely, weaker feedback ejects too few metals, the galaxy over-enriches and it moves above the relation. Similarly, motivated by tentative observational evidence\(^\text{172}\), ref. \(^\text{104}\) explored the impact of IMF variations on the lowest-mass dwarfs. An IMF that is more top-heavy boosts the supernova feedback, but also increases the metal production due to the presence of more massive stars. The net result is

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Dwarfs are more tidally affected than their current orbits suggest. At models being overly strong or it could indicate that the lowest-mass dwarfs are more tidally affected than their current orbits suggest. At higher [Fe/H] at fixed MV, this may be tentative evidence for IMF variations, it could point to current feedback models being overly strong or it could indicate that the lowest-mass dwarfs are more tidally affected than their current orbits suggest. At higher MV, it could point to the important role of radiative transfer. Ref. 106 concluded that models with radiative transfer have slightly higher [Fe/H] at fixed MV than those without. This is because radiative transfer keeps gas warm between starbursts, leading to less vigorous outflows and, therefore, fewer metals escaping into the IGM. Cosmic ray feedback may produce a similar effect. Alternatively, such discrepancies could relate to problems with the assumed chemical yields. Ref. 107 reported no such offset when computing the total metals, rather than just Fe. Either way, it is clear that the [Fe/H]–MV relation encodes a wealth of information about stellar feedback physics that can, at least in principle, be used to test and hone models.

**Distribution and retention of metals in dwarf galaxies.** The stellar metallicity is only one tracer of the total metal budget of dwarf galaxies. For gas-rich systems, we can also measure the metallicity of their ISM and (in some cases) CGM. Furthermore, given their low-mass potentials, we expect that dwarf galaxies will lose a high fraction of their metals through outflows (≥50%; refs. 106,107), distributing them to the CGM (and potentially the IGM). Mapping the distribution of metals from the stars to the ISM and CGM is therefore key to constraining feedback mechanisms.

For those nearby galaxies with detailed stellar metallicities, we often have no comparable gas metallicity, as the majority of local dwarf galaxies are quenched systems, devoid of gas. Estimates of the amounts of metals lost can be obtained using their stellar abundances and chemical evolution modelling. Ref. 108 is one such study with eight Milky Way dwarf galaxies, and estimated that they had ejected ~96–99% of their metals. Gas-phase metallicities, however, can be measured for systems much farther afield and can provide a more complete accounting of the metals in a dwarf. Ref. 109 is a large-scale spectroscopic survey of low-mass local-volume dwarfs to measure the oxygen abundances in their H II regions. Using a robust sample of 38 objects, they showed a tight relation between luminosity and gas-phase metallicities for these objects. Studies such as these present another strong test for feedback models.

A few isolated Local Group dwarfs are gas-bearing, allowing us to compare the fractions of metals in their stars, ISM and CGM directly. Ref. 110 is a study of the CGM of WLM—which has a stellar mass of M = 4.3 × 10^5 M⊙; ref. 111—and found that the majority of metals by mass probably reside there (15–77%), with only ~3% locked in the stars and 6% in the ISM. This is consistent with expectations from simulations, such as ref. 112, which showed that ≥50% of metals are found in the CGM for dwarfs of this stellar mass. Another example is Leo P, which has a stellar mass of M = 5.6 × 10^5 M⊙ (ref. 113). Ref. 114 measured the gas-phase oxygen abundance for Leo P and determined how much oxygen it should have produced on the basis of its resolved SFH. They found that Leo P has retained only 5% of the oxygen it has produced; 25% of that is in stars, while 75% is in the gas phase. This is compared with the 25% retained in more massive galaxies 115.

**The future of the field**

Throughout this Perspective, we have identified key observables with which to confront theoretical models. In this final section, we discuss how future facilities will allow us to make significant progress in mapping stellar feedback and its impact on dwarf galaxies.

First, as highlighted in the ‘The stellar mass–metallicity relation’ section, simulations still tend to underpredict the metallicities of the faintest dwarfs. Understanding this offset is a key challenge. To rule out tidal effects skewing the observational trend, a large sample of isolated ultrafaint dwarfs with measured chemistries is required. The 8.4 m Vera Rubin Observatory will shortly begin its 10 yr Large Survey of Space and Time, optically mapping the southern skies. This survey will allow the detection of ultrafaint dwarfs out to distances exceeding 1 Mpc (ref. 116), where they will be unaffected by ram-pressure and tidal stripping from large host galaxies such as the Milky Way. Depending on their distances, follow-up observations of these objects can be made with existing 10 m or future 30 m telescopes such as the European Extremely Large Telescope. If the offset remains, it may indicate that IMF variations are important for modelling the metallicities of the faintest dwarfs.

![Diagram](image_url)
Second, do dwarf galaxies quenched solely by supernovae exist? A volume-complete sample of isolated dwarf galaxies from the Vera Rubin Observatory will allow us to hunt for these. To determine exactly when they quenched, precision SFHs are needed (using either the HST or future space telescopes). However, the age resolution at the furthest lookback times is typically coarse, even for those nearby galaxies with deep imaging. Progress is rapidly being made in the stellar evolutionary models underpinning these studies81. Further progress on this will help definitively test the impact of external and internal feedback on the faintest galaxies.

Third, new mass modelling techniques that can handle the complications that feedback introduces (such as H I holes) when measuring rotation curves and dark matter masses are needed if we hope to fully exploit the wealth of H I data that will soon come from the SKA/WALLABY (WidefieldASKAP L-band Legacy All-sky Blind Survey). These surveys will give a large, volume-complete survey of faint, H I-rich dwarf galaxies with a known selection function, but without robust tools we cannot fully capitalize on this exciting observational resource.

Finally, a number of upcoming surveys and facilities will allow wide-scale multi-band mapping of the outflows and metallicities of dwarf galaxies. The current HST ULYSSES180 and CLASSY181 programmes are capturing UV spectra of high-mass stars and low-metallicity galaxies, allowing the study of their winds and outflows. The SPRITE UV cubeset is due for launch in 2022, and will map ionizing radiation escaping from star-forming galaxies183. Future integral-field spectrographs installed on ground-based observatories will allow the tracking of galactic winds and outflows at sensitivities not previously permitted. These include the proposed BlueMUSE spectrograph for the Very Large Telescope183. Its high resolution and sensitivity to the blue and UV will make it a powerful probe of feedback and its impact on the ISM and CGM in starbursting dwarfs. In the 2040s, the United States expects to launch the large infrared/optical/UV telescope (recommended in the US 2020 Decadal survey184). This will allow multi-band studies of the stellar and gas contents of dwarf galaxies to large distances, tightening constraints on outflows, mass-loading factors and metal distributions over a wide range of redshifts and environments. Such observations will permit a test of feedback predictions from cosmological simulations that seem at present to overestimate mass loading in the lowest-mass dwarfs (as discussed in the ‘The wind mass-loading factor’ section) and underestimate their starburst duration (as discussed in the ‘Bursty star formation’ section).

The expected advances in instrumentation and models over the next decade listed above should allow significant progress in understanding the properties of, and mechanisms powering, galactic winds in dwarf galaxies. They will also allow us to measure the influence of such winds on the structure, chemistry and dark matter content of these faint galaxies, and lead to a wider understanding of the impact of reionization on low-mass galaxies, and the movement of metals into the CGM.

Data availability
All the data that support the findings of this study are taken from published works (referenced in the text) and are collated into a GitHub repository at https://github.com/justinread/feedback_perspective.

Code availability
The code needed to reproduce all figures in this Perspective is available via GitHub at https://github.com/justinread/feedback_perspective.

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