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Annual Review of Astronomy and Astrophysics
**The Interstellar Medium in
 Dwarf Irregular Galaxies**

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Keywords

dwarf irregular galaxies, interstellar medium, atomic gas, molecular gas,
 CO-dark gas, dust

Abstract

Dwarf irregular (dIrr) galaxies are among the most common type of galaxy in the Universe. They typically have gas-rich, low-surface-brightness, metal-poor, and relatively thick disks. Here, we summarize the current state of our knowledge of the interstellar medium (ISM), including atomic, molecular, and ionized gas, along with their dust properties and metals. We also discuss star-formation feedback, gas accretion, and mergers with other dwarfs that connect the ISM to the circumgalactic and intergalactic media. We highlight one of the most persistent mysteries: the nature of pervasive gas that is yet undetected as either molecular or cold hydrogen, the “dark gas.” Some highlights include the following:

- Significant quantities of HI are in far-outer gas disks.
- Cold HI in dIrrs would be molecular in the Milky Way, making the chemical properties of star-forming clouds significantly different.
- Stellar feedback has a much larger impact in dIrrs than in spiral galaxies.
- The escape fraction of ionizing photons is significant, making dIrrs a plausible source for reionization in the early Universe.
- Observations suggest a significantly higher abundance of hydrogen (H₂ or cold HI) associated with CO in star-forming regions than that traced by the CO alone.

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1. INTRODUCTION

The interstellar medium (ISM) is a dynamic part of galactic ecosystems. Baryons are cycled from the ISM into stars through star-formation processes and are returned to the ISM, circumgalactic medium (CGM), and even intergalactic medium (IGM) through feedback from stellar winds and explosions. With stellar feedback in the weak gravitational potential of a dwarf irregular (dIrr) galaxy, the products of stellar nucleosynthesis are only partially redistributed throughout the ISM; significant quantities escape into the halo, leaving the disk relatively metal poor. Overall, the ISM is complex, dynamic, and multi-faceted.

In this review, we concentrate on the ISM of dIrrs. dIrrs are tiny but they are not just small versions of spiral galaxies. Dwarf irregulars are, in fact, dominated by their ISM (see, for example, **Figure 1**). Their ISMs are primarily atomic hydrogen and helium, but the inner regions could also contain substantial amounts of molecular hydrogen (H_2), and they most often have star formation. Dwarf spheroidal (dSph) galaxies, by contrast, are primarily devoid of an ISM, believed to have been stripped. Thus, we do not discuss dSphs.

Dwarf galaxies were first studied in detail by Reaves (1956) in a survey conducted in the Virgo Cluster. Unfortunately, the class was never truly defined; Reaves refers to them simply as “under-luminous.” In subsequent decades some researchers defined samples based on luminosity, some on surface brightness, and some on baryonic mass. Furthermore, 50 years ago the dwarfs were labeled as Irr-I or Im (Magellanic-type irregulars) or Irr-II (amorphous). However, in recent decades, as dwarfs became better known, those terms have been dropped and researchers rarely define

Interstellar medium

(ISM): the gas and dust mixed with the stars of a galaxy

Circumgalactic medium (CGM):

the gas in the outer halo of a galaxy

Intergalactic medium (IGM):

the gas beyond and between galaxies

Dwarf irregular

(dIrr) galaxy: a galaxy that is small and intrinsically chaotic in appearance, lacking spiral arms and bulges

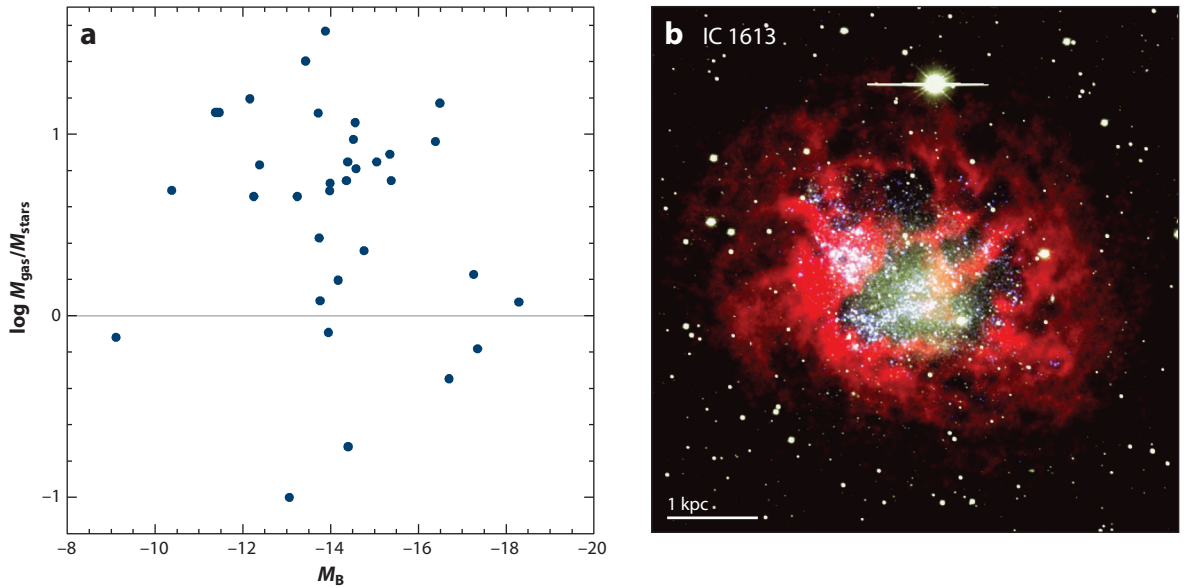


Figure 1

(a) Logarithm of the ratio of atomic gas mass (H_I+He) to stellar mass as a function of galaxy absolute *B* magnitude. These data are from Zhang et al. (2012b) for a subsample of the LITTLE THINGS nearby dIrr galaxies (see Hunter et al. 2012). The horizontal line marks a ratio of 1. (b) False-color image of IC 1613, a typical dIrr in the Local Group. Blue is far-ultraviolet emission, green is *V*-band emission, and red is atomic hydrogen gas emission. Panel *a* adapted with permission from Hunter et al. (2012); copyright 2012 AAS. We thank Lauren Hill for producing panel *b*. Abbreviations: dIrr, dwarf irregular; LITTLE THINGS, Local Irregulars That Trace Luminosity Extremes–The H_I Nearby Galaxy Survey.

“dwarf.” Here, we define what we mean by “dIrr” by looking at two galaxies that represent the extremes to us.

Dwarf irregulars are generally faint, small, low in total mass, low in metallicity, low in dust, and blue in optical colors. However, as a class they exhibit a range in these properties [see lists of dIrrs in Mateo (1998) and Hunter et al. (2012)]. In the Local Group, for example, Leo T has an absolute *V* magnitude M_V of -7 (de Jong et al. 2008), a total baryonic mass of only $6 \times 10^5 M_\odot$, a half-light radius of 170 pc, and a metallicity of $0.025 Z_\odot$ (Irwin et al. 2007, Ryan-Weber et al. 2008, Adams & Osterloo 2018). By contrast, the Large Magellanic Cloud (LMC) has $M_V = -18$ (Macri et al. 2006), a baryonic mass of $3 \times 10^9 M_\odot$ (Besla 2015), a radius at 25 mag arcsec⁻² in the *B*-passband of 4.9 kpc (de Vaucouleurs et al. 1991), and a metallicity of $0.5 Z_\odot$. At another extreme, J0139+4328 is a dwarf with $8 \times 10^7 M_\odot$ of gas but no detectable stars ($M_{\text{stars}} < 7 \times 10^5 M_\odot$; Xu et al. 2023). A typical nearby dIrr is shown in **Figure 1** and others are shown in figures throughout the text.

Although they are tiny compared to spiral and elliptical galaxies, dwarf systems have had an outsized cosmological impact. Simulations of galaxy formation show spirals forming from merging small dark-matter halos, which are essentially dwarf galaxies (see Tosi 2003). The remnants of such accretions are sometimes visible today as stellar streams in galaxy halos (e.g., Ibata et al. 1994). Dwarfs are also likely to have formed the first stars (see the review Bromm & Larson 2004). Lyman-alpha emitters at high redshift have low masses like dwarfs (Ouchi et al. 2020) and may have some properties in common with local dIrrs. Their relatively high escape fraction for Lyman continuum radiation suggests they contributed to the reionization of the Universe (e.g., Asada et al. 2023).

Dwarf spheroidal (dSph) galaxies: galaxies that have a smooth, elliptical appearance

Metallicity: the proportion of atoms heavier than H and He, often measured in the gas phase using optical oxygen nebular lines and calculated as $12 + \log(\text{O}/\text{H})$

Table 1 Major surveys of the interstellar medium of dwarf irregular galaxies

Survey	Telescope–spectral region	Number of dwarfs	Angular resolution (arcsec)	Spectral resolution (km s ⁻¹)	Distance (Mpc)	Reference
HI Survey	Arecibo–HI	123	198	6, 12, 24	6.4–123	Salzer et al. 2002
FIGGS	GMRT–HI	65	5, 22	1.65	1.0–17.4	Begum et al. 2008
THINGS	VLA–HI	12	6	1.3–5.2	2.0–5.3	Walter et al. 2008
ALFALFA	Arecibo–HI	229	210	5	0–49	Huang et al. 2012
LITTLE THINGS	VLA–HI	41	6	1.3, 2.6	0.7–10.3	Hunter et al. 2012
VLA-ANGST	VLA–HI	35	6	0.6–2.6	1.3–4.0	Ott et al. 2012
DGS	<i>Herschel</i> –FIR	50	6–36	150–200 ^a	0.7–191	Madden et al. 2013
ATLAS ^{3D} -MATLAS	WSRT, Arecibo	59	60, 240	16, 10	2–99	Poulain et al. 2022
LGLBS	VLA–HI, continuum	4	6	0.42	0.5–1.0	E. Koch and colleagues ^b

Abbreviations: FIR, far infrared; GMRT, Giant Metrewave Radio Telescope; PACS, Photodetector Array Camera and Spectrometer; SPIRE, Spectral and Photometric Imaging Receiver; VLA, Very Large Array; WSRT, Westerbork Synthesis Radio Telescope.

^aVelocities are related to the PACS spectral survey. The PACS and SPIRE photometric survey resolving power is ~ 2 to 3.

^bE. Koch, A. Leroy, E. Rosolowsky, S. Sarbadhary, L. Chomiuk, et al. (in preparation).

Below, we discuss the various components of the ISM of dIrrs, the processes that take place there, exchange of gas from the CGM and IGM, and outstanding questions. Major surveys related to this topic are listed in **Table 1**. Related reviews include those on the cold ISM in galaxies (Saintonge & Catinella 2022), dust in galaxies (Galliano et al. 2018), the ISM in dwarfs (Henkel et al. 2022), chemical properties of dwarf galaxies (Annibali & Tosi 2022), warm and hot diffuse gas in dwarfs (Bomans 2001), ultrafaint dwarfs (Simon 2019), the structure and evolution of irregular galaxies (Gallagher & Hunter 1984), and star formation in dwarfs (Hunter 2008, Bolatto 2019).

2. ATOMIC GAS

2.1. Large-Scale Distribution

Atomic hydrogen gas densities in dIrrs are generally lower than those in giant spirals. Surface densities in the central regions have peaks on the order of 1–8 $M_{\odot} \text{ pc}^{-2}$, which are comparable with those in the main disk of spirals, 5–10 $M_{\odot} \text{ pc}^{-2}$ (Brinks & Portas 2016, Hunter et al. 2021b). However, spiral galaxies have much higher surface densities closer to the center, whereas dIrrs have lower surface densities everywhere else. Fits of a Sérsic function ($I(R) = I_0 e^{-(R/R_0)^{1/n}}$) to the HI radial (R) profiles of dIrrs find $n \sim 0.2$ –1, where $n = 1$ is exponential; $n < 1$ has a slightly flatter central profile and a faster falloff outside (Hunter et al. 2021b).

Figure 1 shows that most dIrrs are gas rich compared to their stellar mass. The gas associated with galaxies usually extends further than the stars, but it may extend much further than previously realized. Deep HI surveys such as MHONGOOSE (MeerKAT Observations of Nearby Galactic Objects—Observing Southern Emitters), with column density sensitivities better than 10^{18} cm^{-2} , find up to 25% of a galaxy’s gas in the far outer regions at very low column densities (see, for example, Sardone et al. 2021). It is not clear what role this outer disk gas plays in galactic evolution.

Gas in all but the smallest dIrrs exhibits regular circular rotation, often with a near-linear rise in rotation speed away from the center (Lo et al. 1993a,b; Oh et al. 2015; Iorio et al. 2017). Observations of the HI kinematics of the low-mass end of dIrrs show the difficulties in fitting a rotation curve to these galaxies (e.g., Oh et al. 2015, McNichols et al. 2016). Simulations also suggest that at the lowest masses ($< 10^8 M_{\odot}$), dIrrs should be dispersion dominated because of high turbulence from stellar feedback and heating by the cosmic UV background, which suppresses

high angular momentum accretion (El-Badry et al. 2018). For those galaxies with regular rotation, the ISM does not undergo the levels of shear that occur in spirals with flat rotation curves, and this low shear means that ISM structures, such as shells and holes, can last longer than in the highly sheared regime of spiral disks.

2.2. Structures

The ISM of dIrr galaxies is not smoothly distributed. It contains clouds, holes, and shells. There is also flaring of the H I disk and turbulence throughout the gas. Here, we discuss the various structures in the ISM and the relationship of the ISM to star formation and the stellar disk.

2.2.1. Clouds. Atomic gas consists of cool and dense clouds, often in filaments, with lower-density, warmer gas between them. Power spectra of H I emission from the Small Magellanic Cloud (SMC) and the Large Magellanic Cloud (LMC)¹ actually show a hierarchy of structures, so the cloud–intercloud model is oversimplified (Stanimirović et al. 1999, Elmegreen et al. 2001). Dense regions that might be identified as discrete clouds several hundred parsecs in size were identified in 9 dIrrs by Lo et al. (1993a,b). Kim et al. (2007) identified 468 H I clouds with masses of 10^3 to $10^5 M_{\odot}$ in the LMC, and Hunter et al. (2019) identified 814 H I clouds with masses of 10^3 to $10^7 M_{\odot}$ in 40 nearby dIrrs. In the Hunter et al. study, the clouds constitute 2% to 53% of the total H I mass of the host galaxy. Many of these clouds are in the outer regions, beyond one disk scale length, and not all of them are self-gravitating unless they contain significant amounts of molecular or cold atomic gas.

2.2.2. Holes, shells, and outflows. The ISM of dIrrs is especially characterized by holes, giving them a high porosity (Dimaratos et al. 2015, Cormier et al. 2019). In 41 gas-rich dIrrs from LITTLE THINGS (Local Irregulars That Trace Luminosity Extremes—The H I Nearby Galaxy Survey), Pokhrel et al. (2020) identified 306 holes in H I ranging in diameter from the resolution limit of 40 pc up to 2.3 kpc with expansion speeds up to 30 km s^{-1} . The H I surface porosity (ratio of total area covered by holes to total area covered by H I out to a column density of $5 \times 10^{19} \text{ atoms cm}^{-2}$) is as high as 15%. In another sample of nearby spirals and dwarfs, Bagetakos et al. (2011) detected more than 1,000 holes in 20 galaxies with sizes of 0.1 kpc to 2 kpc and ages of 3 Myr to 150 Myr; 23% of these fell beyond the optical radius. Relatively low shear, reduced disk gravity, and a relatively large-scale height in dIrrs enables feedback-driven shells to grow larger compared to the disk scale length than in spirals (Brinks et al. 2002). Sometimes the shells break out of the disk altogether (see **Figure 2** below).

Giant shells in dwarf galaxies often contain secondary star formation triggered by the compression of gas in the surrounding region. Examples are in IC 2574 (Walter et al. 1998, Egorov et al. 2014), DDO 47 (Walter & Brinks 2001), Haro 14 (Cairós & González-Pérez 2017a), Tololo 1937-423 (Cairós & González-Pérez 2017b), Holmberg I (Ott et al. 2001, Egorov et al. 2018), and Holmberg II (Puche et al. 1992, Egorov et al. 2017; see **Figure 3** below). (See Zucker et al. 2022 for a Solar Neighborhood example.) Simulations of this process are in Kawata et al. (2014) and Lahén et al. (2019). Constellation III in the LMC is a spectacular region that formed stars 12–16 Myr ago and blew a 1.4 kpc hole in the ISM. Stars have formed in the surrounding shell over the past 6 Myr (Dolphin & Hunter 1998). Some holes in dIrrs are large enough to dominate the entire galaxy. In DDO 88 there is a 2 kpc hole centered on the optical galaxy with a radius of half of the optical size of the galaxy. The shell surrounding the hole contains 30% of the total H I

¹The SMC and LMC are two dIrrs that are gravitationally interacting with each other and with the Milky Way. The LMC is at the massive end of dwarfs, and the SMC has been significantly disturbed by the interaction.

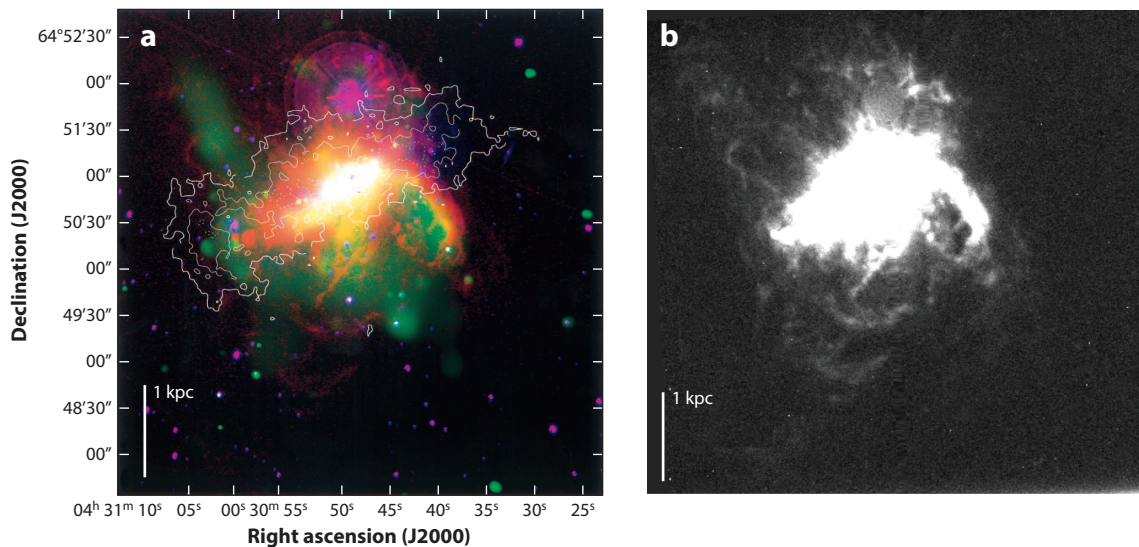


Figure 2

(a) False-color image of NGC 1569 showing X-ray (green), H α (red), 6450 Å continuum (blue), and H I (dashed white line) emissions. (b) H α emission image of NGC 1569 that shows the large-scale filaments. Panel a adapted with permission from Martin et al. (2002); copyright 2002 AAS.

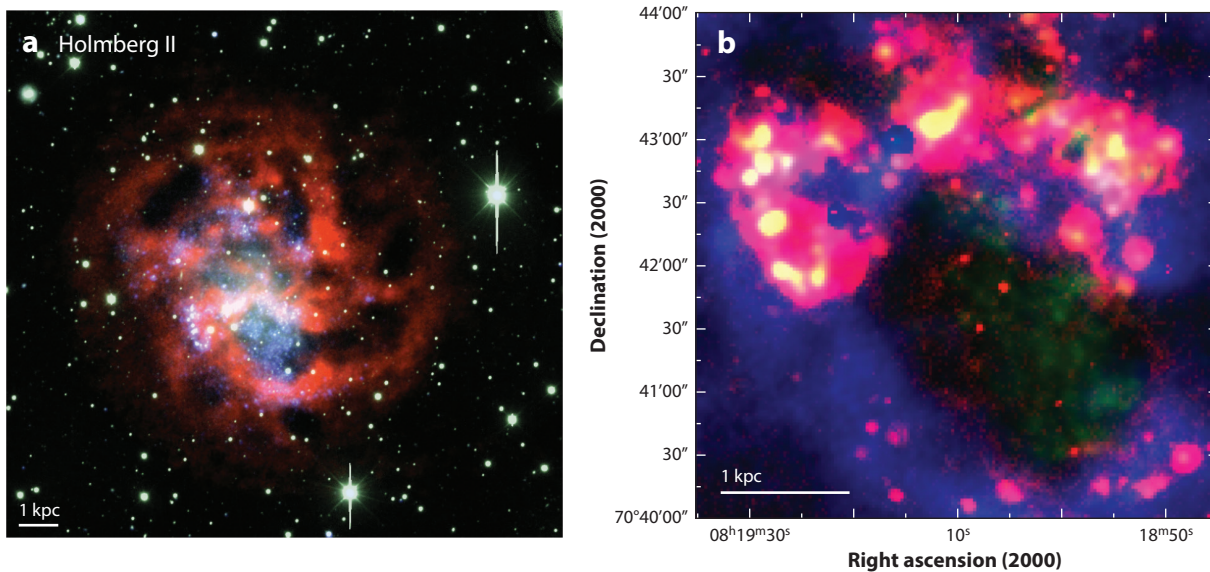


Figure 3

(a) False-color image of Holmberg II. Blue is far-ultraviolet emission, green is V -band emission, and red is atomic hydrogen gas emission. (b) Giant gas shell with peripheral star formation in Holmberg II, with red, green, and blue corresponding to H α , far-ultraviolet (GALEX), and H I 21-cm (LITTLE THINGS) emission, respectively. This shell is centered on the prominent hole just south of the center of the galaxy. We thank Lauren Hill for producing panel a. Panel b adapted from Egorov et al. (2017) with permission from the lead author and OUP. Abbreviations: GALEX, *Galaxy Evolution Explorer*; LITTLE THINGS, Local Irregulars That Trace Luminosity Extremes–The H I Nearby Galaxy Survey.

(Simpson et al. 2005). The impact of giant shells on total star formation is not known. Only a small fraction of the star formation (<15%) is in obvious shells (Bolds 2020), and the star-formation rate (SFR) does not correlate with the porosity (Pokhrel et al. 2020).

Beyond the immediate shells with triggered star formation, the porosity caused by holes allows far-ultraviolet (FUV) photons from young stars to travel throughout a galaxy, heating the ISM and inhibiting more star formation (Silk 1997, Forbes et al. 2016). Another consequence of this porosity is that star formation moves around the galaxy on long time and spatial scales as regions are hollowed out by stellar feedback and take time to fill back in. Combined with relatively rapid motions from feedback and aggravation from outside, the effects can be severe, as in DDO 187 and NGC 3738, which have a blue star-forming half and a redder half with only older stars (Hunter et al. 2018). Heating and dynamical perturbations can also lead to “gasy” star formation (Lee et al. 2007), where the SFR increases and decreases as conditions periodically favor and then inhibit star formation on a large scale. This can even lead to a reshuffling of the H I relative to the stars in which the gas becomes more centrally concentrated (Simpson & Gottesman 2000) or of the stars themselves as stellar feedback forces radial migration of stars outward (El-Badry et al. 2016).

Holes are generally believed to be formed by feedback from massive stars. These stars dump copious quantities of mechanical energy into the ISM from stellar winds and supernovae (Tenorio-Tagle & Bodenheimer 1988, Vorobyov & Basu 2005). However, the story may sometimes be more complicated than holes resulting from a single star-formation event. Multiage stellar populations are inside the H I holes in Holmberg II, suggesting feedback over a period of 100 Myr (Weisz et al. 2009). Kepley et al. (2007) suggested that the central H I depression in Wolf–Lundmark–Melotte (WLM) could have formed by feedback over the past 130 Myr. Multiple generations including triggered star formation were found to enlarge the holes in 5 dIrrs by Warren et al. (2011). Starbursts occasionally last for 500 Myr (McQuinn et al. 2010).

Intense stellar feedback can result in very large holes that break out of the disk and sometimes result in outflows into the CGM (Marasco et al. 2023). NGC 1569 is a good example of a nearby (2 Mpc) dIrr with massive star clusters (Hunter et al. 2000), energetic feedback, a kiloparsec-scale hole, and outflow in a hot wind. Large-scale (up to several kiloparsecs) H α filaments extend out of the plane of the galaxy (Hunter et al. 1993a,b; see **Figure 2**). Spectral analysis by Hunter & Gallagher (1997) shows that the large-scale filaments are photoionized, probably by photons escaping H II regions located up to a kiloparsec away. The implied escape fraction is on the order of 25%. Heckman et al. (1995) observed that about half of the X-ray flux from this galaxy originates in a ~ 2 kpc halo, with X-ray spurs along the galaxy minor axis adjacent to the long H α filament. The outflow speed reaches 200 km s $^{-1}$ (see also Westmoquette et al. 2008), and the outflow age is comparable with the starburst age of $\sim 10^7$ years. Heckman et al. (1995) and Martin (1998) suggest that the expanding material could eventually blow out into the halo. Spectroscopic observations by Martin et al. (2002) found that the X-ray wind is metal enriched, having a solar abundance of α elements, which requires nearly all of the oxygen made in the starburst to go into the wind, whereas the disk H II regions are 0.2 Z_{\odot} . The dust-to-gas mass ratio (DGR) is higher on the periphery of the H I hole (Lianou et al. 2014). The magnetic pressure in NGC 1569 is approximately in equilibrium with the other ISM components (Kepley et al. 2010).

NGC 1705 (Hensler et al. 1998), I Zw 18 (Martin 1996, Hunt et al. 2005), NGC 5253 (Martin & Kennicutt 1995), IC 2574 (Walter et al. 1998), NGC 4214 (Hartwell et al. 2004), and IC 10 (Heesen et al. 2015) are galaxies similar to NGC 1569 with massive star-forming regions and large bubbles of soft X-ray emission. In some cases, the energy and momentum in the bubble is enough to push the hot gas and local ISM out of the galaxy (Marlowe et al. 1995). This “blow-out” can remove a significant fraction of the metals produced in the starburst (Dekel & Silk 1986), as shown by numerical simulations (De Young & Heckman 1994; for recent work, see Emerick

et al. 2019 and references therein) and suggested by observations of NGC 1569 (Martin et al. 2002), NGC 625 (Cannon et al. 2005), I Zw 18 (Martin 1996, Hunt et al. 2005), and Holmberg I (Ott et al. 2001). Outflows have also been observed in the LMC (Ciampa et al. 2021) and SMC (Di Teodoro et al. 2019). McQuinn et al. (2019) observed winds in six star-bursting dwarf galaxies using deep H α observations, and Grimes et al. (2005) observed X-rays from winds in seven dwarfs.

Outflows into the CGM, such as those seen so dramatically in NGC 1569 and NGC 1705, allow Lyman continuum photons to escape from the cavities (Fujita et al. 2003) and may carry the magnetic field out with it too (Chyży et al. 2016). In 43 low-mass galaxies ($10^8 M_{\odot} < M_{\text{stars}} < 10^{10} M_{\odot}$), Bordoloi et al. (2014) observed halo carbon masses exceeding the carbon masses in the ISM and stars, implying that considerable quantities of heavy elements are expelled into the CGM in these events. A metal-rich halo in IC 1613 is also shown by Zheng et al. (2020). Cosmological simulations that include the multiphase ISM, star formation, and stellar feedback find large inflow and outflow rates in the CGM of dwarfs, with a net inflow of gas from the IGM (Li et al. 2021). The inflow rates are comparable with the SFRs in the disks (see Section 6.2), suggesting that the two are coupled. Significant blow-out can also change the gravitational potential in the disk as gas outflows redistribute mass, causing stars and dark matter to scatter outward (El-Badry et al. 2016) and converting a cuspy dark matter center to a core (Governato et al. 2012).

2.2.3. Thickness. Dwarf irregular galaxies are generally considered to be disk galaxies, but their disks are thicker relative to their sizes than in spirals by a factor of 2 to 5 (Brinks et al. 2002, Patra 2020). This is true for stars (Hodge & Hitchcock 1966, Johnson et al. 2017), gas and dust (Walter & Brinks 1999, Dalcanton et al. 2004, Roychowdhury et al. 2010, Elmegreen & Hunter 2015), and particularly for dwarfs supported more from turbulence than rotation (Kaufmann et al. 2007, Wheeler et al. 2017). Less massive dwarfs are apparently puffier than more massive dwarfs (Johnson et al. 2017). In a study of H I power spectra, Zhang et al. (2012a) found that LITTLE THINGS dwarfs with absolute magnitudes M_B brighter than -14.5 are relatively thinner than lower-mass dwarfs.

The H I in dIrrs also flares or warps more than in spirals (Kepley et al. 2007, Patra et al. 2014, Szołkowski et al. 2019, Patra 2020). For example, Banerjee et al. (2011) determined H I scale heights for four dIrrs in the THINGS sample. One of the dwarfs has a scale height of about 450 pc throughout the disk, whereas the other three flare beyond 3–4 disk scale lengths to as high as 1 kpc scale height. Flaring is to be expected in most galaxies because the gas velocity dispersion remains approximately constant at large radii while the disk surface mass density declines exponentially. Deep H I and H α mapping of an edge-on dwarf by Kamphuis et al. (2011) found both neutral atomic and ionized gas well above the plane of the galaxy: H α gas extends to 655 pc and H I to 1.8 kpc. In a study of 23 LITTLE THINGS dwarfs, Patra (2020) found that scale heights rise exponentially with radius from a few hundred parsecs around the centers to a few kiloparsecs at the edges. These thicknesses yield a median axial ratio that is three times that of the Milky Way and allow stellar radiation to transfer more effectively through the disks of dIrrs than in denser spirals.

Power spectra of the LMC H I reveal a slope transition at ~ 100 pc scale that suggests an H I disk of this thickness, with 2D turbulence on larger scales having a shallow slope and 3D turbulence on smaller scales having a steeper slope (Elmegreen et al. 2001). The steep part goes to larger scales in the outer regions, suggesting a flare (Szołkowski et al. 2019).

A thick gas disk affects the ability of the dIrrs to form stars. Relatively thick disks diminish radial instabilities by diluting the radial component of the gravitational force per unit surface density (Vandervoort 1970). 3D processes should be relatively more important (Elmegreen & Hunter 2015, Bacchini et al. 2020). For example, Elmegreen (2011) noted that, for a given column

density, a thick disk inhibits the instabilities that can lead to cloud formation, and Elmegreen & Hunter (2015) developed a star-formation law based on 3D gaseous gravitational processes and molecule formation that is more appropriate to dIrrs.

2.3. Turbulence

H_I linewidths are the result of thermal and bulk motions from turbulence and massive stellar feedback. Characterizations of the H_I motions have used third- and fourth-order moments, i.e., skewness and kurtosis of the line profiles. Burkhart et al. (2010) compared observations of the SMC to simulations and determined that 90% of the H_I motions are sub- or transonic. The exception is for supersonic motions around the edges of the bar. Maier et al. (2017) applied this technique to the LITTLE THINGS galaxies and found that turbulent speeds were close to sonic. In a study of 6 dwarfs using H_I power spectra, Dutta et al. (2009) found that several showed 2D turbulence on scales larger than the scale height and others showed 3D turbulence.

What drives turbulence in galaxies? Given the obvious energetic feedback from massive stars, turbulence might be expected to come from this feedback energy. Inversely, we might expect turbulence to compress the gas and initiate new star formation. The hierarchical clustering in both space and time of young stars, associations, and clusters in the LMC and nearby spiral galaxies suggests that turbulence helps make star-forming clouds (Efremov & Elmegreen 1998, Grasha et al. 2017, Miller et al. 2022). The velocity dispersion in the ionized gas is the result of thermal motions combined with young stellar feedback (Moiseev et al. 2015).

However, spatial correlations between star formation and the kinetic energy density (KED) of the neutral ISM are not obvious. For example, Hunter et al. (2021a) cross-correlated KED images with SFR density Σ_{SFR} images of LITTLE THINGS dwarfs and found no correspondence. They further compared the excess KED above the radial average with the excess Σ_{SFR} and again found no correlation. In addition, the excess velocity dispersion in star-forming regions is small. A similar study of THINGS spirals found the same result (Elmegreen et al. 2022). Their conclusion was that stellar feedback energy mostly disrupts molecular clouds without affecting H_I turbulence on large scales. Similarly, Stilp et al. (2013b) compared H_I KED measures with time-resolved star-formation histories and concluded that the KED correlates only with star formation from 30–40 Myr ago, the lifetime of the lowest-mass supernova progenitor. In contrast, Hunter et al. (2022) found in four nearby dIrrs that on scales of 400 pc, H_I turbulence correlates with star formation from 100–200 Myr ago.

There are other candidates to drive turbulence in the ISM of galaxies, this being an issue for all disk galaxies, not just dwarfs. Klessen & Hennebelle (2010) suggest from simulations that radial accretion is able to drive turbulent motions in spiral galaxies if the accretion rate is comparable with the SFR, especially in the outer disk. However, in dwarfs the accretion rate would have to be much larger than the SFR, so other sources of turbulence are needed. Stilp et al. (2013a) examined various potential drivers, such as star formation, gravitational instabilities, magnetorotational instabilities, and accretion, and concluded that none of these are capable of driving turbulence in low- Σ_{SFR} regions such as dIrrs.

2.4. Cold H_I

The ISM of dIrrs, like that of spirals, is multiphase with a cold neutral medium (CNM; $T \sim 40$ –200 K in the Milky Way) embedded in a warm neutral medium (WNM; $T \sim 5,000$ –8,000 K) (e.g., Andersen & Burkert 2000). Bialy & Sternberg (2019) show, however, that the characteristics of the multiphase medium depend on the metallicity. At very low metallicities of 10^{-3} – $10^{-2} Z_{\odot}$, the cooling rate decreases as metallicity decreases, whereas the heating rate is nearly independent of

the metallicity, resulting in a need for higher pressures and densities to form a CNM phase. At extremely low metallicities of 10^{-4} – $10^{-5} Z_{\odot}$, a multiphase medium cannot exist. Interestingly, at moderate metallicities $>0.1 Z_{\odot}$, the CNM may be colder.

Cold H I may be more important to a galaxy than the total H I because the cold H I is more directly connected to star formation (Ianjamasimanana et al. 2012). Even the tiny dIrr Leo T has a cool H I component in its ISM (Ryan-Weber et al. 2008). However, observationally there are differences between the cold H I content in dIrrs and spirals. In a study of the cold H I in the SMC through absorption spectra, Dickey et al. (2000) found that it constitutes only 15% of the total H I, which is about half that in the Solar Neighborhood. However, much of this gas is in dense, ~ 10 – 40 K clouds that would be molecular if they were in the Milky Way. Dempsey et al. (2022) found a cold gas fraction of 11% in the SMC. We return to this point in Section 4.1.4.

Several studies have examined cold H I in dIrrs by deconvolving the H I line profiles into broad ($\sigma \sim 10$ km s $^{-1}$, warm) and narrow ($\sigma \sim 2$ – 5 km s $^{-1}$, cold) components. Young & Lo (1996, 1997) and Young et al. (2003) examined the H I in 7 nearby dIrrs and found that the cold component was generally concentrated in a few $10^6 M_{\odot}$ clumps. One dwarf, LGS 3, which is notable for having no H II regions, lacked a cold phase altogether. However, no correlation was found between the quantity of cold H I and the SFR, and not all cold H I is associated with star-forming regions (see also Begum et al. 2006). Park et al. (2022) fit cool and warm, bulk (i.e., following the rotation curve) and nonbulk H I to the line profiles in NGC 6822 and found fractions of only 3.8% and 0.8% for the cool-bulk and cool-nonbulk components, the rest being warm H I. Using H I power spectra applied to channel maps of LITTLE THINGS dIrrs, Zhang et al. (2012a) found that most of the cool H I is in the inner disks, although the thermal dispersion of the coolest H I component is smaller than 1.8 km s $^{-1}$, the channel resolution of the data, making this gas hard to detect (see Section 4.1.4). Cold H I has even been found in the Magellanic Bridge from absorption studies (Kobulnicky & Dickey 1999).

2.5. Relationship of H I to Star Formation and the Stellar Disk

In dIrrs the azimuthally averaged surface density of star formation follows the drop with radius of the stellar surface density better than the gas surface density, even though the gas is the material for star formation (Hunter & Elmegreen 2004, Leroy et al. 2008). Nevertheless, the general relationship between atomic H I and star formation is captured in the Kennicutt–Schmidt relationship $\Sigma_{\text{SFR}} \propto (\Sigma_{\text{gas}})^n$ with $n \sim 1.3 \pm 0.3$ (Schmidt 1959, Kennicutt 1989), where surface density is measured globally or in kiloparsec-sized regions. This relationship was established for spiral galaxies, but Bigiel et al. (2010) extended it to the outer parts of spirals and dwarfs, regimes of lower SFR, and lower gas densities. They found that the relationship in these extreme regimes is steeper ($n \sim 1.7$) than in the inner parts of spirals, and the star-formation efficiency (the rate per unit gas) is lower. However, a molecular version of the Kennicutt–Schmidt Law shows that $\Sigma_{\text{SFR}} \propto \Sigma_{\text{H}_2}$ in both spirals and dwarfs (Schruba et al. 2011).

How far out in radius and how low in gas density can the SFR go? Hunter et al. (2016) identified the most remote young stellar regions, observable as FUV knots, in 37 LITTLE THINGS galaxies. They found regions with ages under 20 Myr out to 1–8 disk scale lengths, where the minimum H I surface density was about $1 M_{\odot} \text{ pc}^{-2}$. Taylor & Webster (2005) suggested that galaxies with masses $>10^6 M_{\odot}$ in gas form stars until the radiation field heats and stabilizes it (but see J0139+4328 with $8 \times 10^7 M_{\odot}$ of gas and no observed stellar component; Xu et al. 2023). Thus, a tiny galaxy like Leo T, with multiple generations of stars and a gas mass of $4 \times 10^5 M_{\odot}$ (Ryan-Weber et al. 2008), must represent nearly the minimum galaxy for self-regulated star formation.

The Kennicutt–Schmidt relation shows the quantitative correlation between Σ_{SFR} and Σ_{gas} , but it does not reveal how star-forming clouds form. The problem with star formation in dIrrs is

that the gas densities are low, even in the central regions, and there are no spiral density waves to pile gas up. What mechanisms could make density enhancements in order to form clouds? An important way to make clouds in spiral galaxies is through gravitational instabilities, which are quantified in terms of the ratio of a critical gas density to the actual gas density, Q (Toomre 1964). Q is a function of the epicyclic frequency, and so a function of the rotation curve. Gas densities above the critical gas density on large scales are unstable and break up into clouds; gas below the critical gas density is stable. Hunter et al. (1998) found that the H I gas is stable almost everywhere in dIrrs. In NGC 2366, for example, the star-forming regions are associated with H I peaks that are close to the critical density even though the average surrounding gas density is below it (Hunter et al. 2001a). However, unseen molecular gas, i.e., gas that is not clearly associated with CO emission (see Section 4.1.4), could make the ISM more unstable (Hunter et al. 2019).

There are other processes for producing gas density enhancements that could be important in dwarfs: stellar feedback, turbulence, and external gas accretion. As discussed in Section 2.2.2, feedback from massive stars can pile gas into shells and trigger the formation of a next generation of stars (see **Figure 3**). This process does take place in dIrrs, but only a small percentage ($<15\%$) of the star formation in each galaxy is located in obvious shells (Bolds 2020). Turbulence is another way to make density enhancements that become self-gravitating, but there is no direct evidence for particular star-forming events triggered in this way (see Section 2.3). By contrast, cloud–cloud collisions may be considered a form of turbulence, and there are many examples suggesting cloud collisions trigger star formation (see the review Fukui et al. 2021). It has also been proposed that accretion of gas from the CGM or IGM furthers star formation (see, for example, simulations by Li et al. 2021), but, again, there is no observational evidence for wide-spread accretion of this sort onto dwarfs (or spirals; however, see the example of tadpole galaxies in Section 6.2). Star formation is a local process that depends on global conditions (Hunter 2008), but aside from the formation of giant shells, we have yet to find observational evidence for what processes are most important in initiating the local conditions that are the first step to making star-forming clouds. Perhaps cloud formation is from a combination of processes that are difficult to recognize at the initial stages.

Because stars form out of the gas, we expect that features in the stellar disk would be accompanied by changes in the gas disk. One feature of stellar disks of both spirals and dwarfs is that the stellar surface brightness profiles frequently show a “break,” where the exponential falloff with radius abruptly changes slope (for example, in dwarfs see Herrmann et al. 2013). In most disks the bend is downward (Type II) but in some it is upward (Type III). Few disks show no break (Type I). For dIrrs these surface brightness breaks are also present in stellar mass density profiles. So what happens at the break? There is no correlation between the H I surface density or features of the gas rotation curves and the location of the break (Hunter et al. 2021b). Currently, we do not understand the connection between the breaks in stellar exponential disks and the star formation and gas characteristics.

3. STAR-FORMING REGIONS AND IONIZED GAS

Most dIrrs have H II regions where star formation takes place, and dense clouds are ionized by young massive stars. The H II region luminosity function is a power law for dIrrs as it is for spirals, but the power law is shallower in dIrrs (slope $\sim -1.5 \pm 0.1$ for those with turnovers or $\sim -1 \pm 0.1$ for those without) than in spirals (~ -1.9) (Youngblood & Hunter 1999, Thilker et al. 2002, Oey et al. 2003). Also, the upper luminosity cutoffs are lower in dIrrs, which do not often have supergiant H II regions. However, nearby dIrrs do frequently have complexes of smaller H II regions compared to nearby spiral galaxies. In fact, most of the H α luminosity from H II regions comes from regions that are smaller than 10 times the Orion nebula. Fourier transform power spectra of dIrr H α emission, taken along the major axes, have revealed a universal slope inside

X_{CO} : ratio of H_2 column density to integrated CO line strength

α_{CO} : ratio of average molecular surface density to integrated CO line strength or molecular mass to CO luminosity for unresolved clouds

HII regions that is consistent with Kolmogorov turbulence (Willett et al. 2005). Cormier et al. (2015) also found that HII regions in dwarfs have harder radiation fields than in spirals owing to the impact of lower metallicity on stellar emission; specifically, main sequence temperatures are hotter owing to reduced line blanketing and blocking in stellar atmospheres (Madden et al. 2006).

In addition, dIrrs, like spirals, contain diffuse ionized gas (DIG) outside of HII regions. Analysis of the DIG in 14 dIrrs by Martin (1997) showed that most of the DIG is photoionized by massive stars in star-forming regions and is a result of the porosity of the ISM in these galaxies (see also Hidalgo-Gómez 2007, Polles et al. 2019). Choi et al. (2020) showed that the fraction of ionizing photons escaping the galaxy is about 25% for NGC 4214. Multiphase modeling of the ISM of dwarfs by Ramambason et al. (2022; see also Cormier et al. 2019) showed that the structure and porosity varies with metallicity. The escape fraction of ionizing photons goes up as the metallicity goes down, with escape fractions reaching as high as 60%. This suggests that dIrrs and similar systems could provide ionizing photons to the IGM to be a source of reionization in the early Universe (Enders et al. 2023).

In some dIrrs there are also embedded star-forming regions that radio continuum or IR observations have revealed (for example, Hindson et al. 2018). NGC 5253 contains a large HII region and massive star cluster with thousands of O-type stars that are detected in 7 mm continuum and near-IR emission (Turner & Beck 2004). Mid-infrared (MIR) observations of NGC 1569 have revealed an embedded compact source that is optically thick in the radio band and may contain nearly a thousand O-type stars (Tokura et al. 2006). Centimeter radio observations of NGC 4449 have revealed numerous thermal radio sources with ages less than 5 Myr and stellar masses on the order of $10^4 M_{\odot}$ (Reines et al. 2008, Calzetti et al. 2023). These are all large star-forming regions found in small galaxies with high SFRs.

Coronal line emission has been found in dwarfs as part of the Sloan Digital Sky Survey, with the dwarfs preferentially having emission lines with the highest ionization potentials (Reefe et al. 2022). These emission lines could come from central black holes with hotter accretion disks than those around supermassive black holes in spiral galaxies. Bohn et al. (2021) identified 5 galaxies at the massive end of the dwarf range with coronal line emission that is likely due to AGNs accompanied by outflows, and Hatano et al. (2023) have found the signature of a dust torus around a massive black hole in the dwarf SBS0335-052E. The relative population of AGNs in dwarfs and the effect of AGN activity on their ISM are not known.

4. MOLECULAR GAS

4.1. Observations

In the Milky Way, we see that star formation takes place in clouds of molecular gas. For that reason, molecular gas is crucial to the evolution of galaxies. For the reasons outlined below, observations of molecular gas in dIrrs have been very difficult.

4.1.1. Early discoveries. CO is weak in low-metallicity galaxies. It took over a decade longer to detect CO in the SMC (Israel et al. 1986) than in the LMC (Huggins et al. 1975), which have metallicities of $0.2 Z_{\odot}$ and $0.5 Z_{\odot}$, respectively. Early low-resolution surveys (Cohen et al. 1988, Rubio et al. 1991) and high-resolution maps (Israel et al. 1993; Rubio et al. 1993a,b) of the Magellanic Clouds eventually demonstrated the influence of metallicity, dust, and UV radiation on CO emission. Lequeux et al. (1994) concluded that the CO parts of dense cloud complexes in the SMC shrink to the inner cores while HI and possibly H_2 surround them. This is still the primary model at low metallicity, discussed now in terms of elevated ratios of H_2 column density to integrated CO line strength, X_{CO} , and molecular surface density to integrated CO line strength, α_{CO} , or, equivalently, molecular mass to CO luminosity.

The third dIrr detection, NGC 1569, was made with the 14-m telescope at the Five College Radio Astronomy Observatory by Young et al. (1984). This galaxy was soon followed by NGC 3738, NGC 4214, and NGC 4449 (Tacconi & Young 1985), and six more, including three blue compact dwarf (BCD) galaxies, in a survey of 15 dIrrs by Tacconi & Young (1987). At the same time, CO in IC 10 was discovered by Henkel et al. (1986) with the 7-m telescope at AT&T Bell Laboratories and mapped in 5 points by Ohta et al. (1988) with the 45-m telescope of the Nobeyama Radio Observatory (NRO). The first detection in a galaxy smaller than the LMC (other than the SMC), NGC 3077, was made with the 30-m Institut de Radio Astronomie Millimétrique (IRAM) telescope by Becker et al. (1989).

Larger early surveys included NGC 6822 by Wilson (1992), who used the National Radio Astronomy Observatory (NRAO) 12-m telescope; 13 BCDs and 2 dIrrs by Sage et al. (1992) with IRAM; NGC 6822 and NGC 4214 by Ohta et al. (1993) with NRO; and He 2–10 by Baas et al. (1994) with the 15-m Swedish-ESO Submillimetre Telescope (SEST) and by Kobulnicky et al. (1995) with the first CO interferometry using Owens Valley Radio Observatory. A few more dIrrs by Israel et al. (1995) with the SEST and NRAO telescopes, in addition to [CII] observations of IC 10 by Madden et al. (1997) with NASA's Kuiper Airborne Observatory (KAO), led these authors to conclude that significant H₂ in dIrrs was unseen.

In the two decades since these early discoveries, there have been many observations of molecules of various types in dIrrs. In the first large survey, Leroy et al. (2005) searched for CO(1–0) in 121 galaxies of average dynamical log mass ~ 9.6 (in solar mass) and detected 28; the lowest-mass detections were NGC 5338 (Hubble-type SB0) and NGC 3913 (Sc). Schrubba et al. (2012) observed 16 local dwarfs in CO(2–1) and detected 5 by stacking the spectra. Cormier et al. (2014) surveyed 6 dwarfs in several CO transitions and detected 5, all with metallicities above that of the SMC; their one galaxy with SMC-type metallicity, NGC 4861, was undetected.

The most recent SMC surveys are by Saldaño et al. (2023) at 9 pc resolution and Ohno et al. (2023) at 2 pc. Ohno et al. found that molecular clouds in the SMC have a mass spectrum similar to that of the Milky Way, with a slope for dN/dM equal to ~ -1.7 , and they have slightly narrower linewidths for their size, $\sigma_v \sim 0.5R^{0.5}$ for radius R in parsecs and velocity dispersion σ in kilometers per second, compared to $\sim 0.7R^{0.5}$ in the Milky Way. Saldaño et al. derived a CO-to-H₂ conversion factor $\alpha_{\text{CO}} = 10.5 \pm 5 M_{\odot} (\text{km s}^{-1} \text{pc}^2)^{-1}$ assuming virialized clouds for the total mass and $28 \pm 15 M_{\odot} (\text{km s}^{-1} \text{pc}^2)^{-1}$ using the dust emission for the mass. These are larger than that in the Milky Way by factors of 2.4 and 6.5.

4.1.2. The lowest metallicities. CO has been mapped in only a few galaxies with metallicities comparable with or lower than that of the SMC. The observations are summarized in what follows with an emphasis on unique features for each galaxy. Generally, parsec-scale observations are necessary to resolve individual CO clouds, which tend to be much smaller than their CO-dark envelopes and generally a few parsecs in size. If we consider the large-scale gas concentrations to be composite clouds, then the ratio of this cloud mass to the mass of the CO-luminous part can be in the hundreds for dIrrs; it can be even larger for the lowest metallicities, suggesting extensive peripheral gas unobserved in H_I, H₂, or CO. This peripheral gas is still visible in other forms, such as dust or [CII] emission (see below), but it is not as prominent in CO as it is in the Milky Way. Nevertheless, the CO parts of low-metallicity clouds are very similar to scaled-down versions of CO clouds elsewhere: They have comparable densities and extinctions, and they are close to virialized.

Shrinking CO cores inside dense cloud complexes can be characterized by variations in the CO(1–0)-to-H₂ conversion factor. Galactic conversion factors are typically taken to be $X_{\text{CO}} = 2.0 \times 10^{20} \text{ H}_2 \text{ molecules cm}^{-2} (\text{K km s}^{-1})^{-1}$ and $\alpha_{\text{CO}} = 4.3 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$, where the

Blue compact dwarf (BCD) galaxies:

centrally concentrated galaxies that have high surface brightness and are actively forming stars

latter includes a factor of 1.36 for He and heavy elements (Bolatto et al. 2013). Note that α_{CO} written this way may be viewed as a total cloud mass per unit CO luminosity, L' in $\text{K km s}^{-1} \text{ pc}^2$, but is equivalently written as a total gas surface density per unit CO line integral with units of $\text{M}_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$. The first way allows one to consider undetected gas surrounding the CO source, as in a cloud envelope with CO in the core.

Derivations and caveats with the conversion factors are discussed in Section 4.2. These factors tend to increase with decreasing metallicity, clumpiness, and increasing physical scale, as the CO-emitting gas becomes a smaller fraction of the total. They also increase with specific SFR (sSFR), as the excess FUV photons penetrate further into the cloud envelopes, disassociating the molecules more (Section 4.2.3). These dependencies make it ambiguous to plot a quantity like α_{CO} against just one parameter representing dIrrs, such as metallicity.

- **NGC 6822** ($12 + \log \text{O}/\text{H} = 8.02$ or $0.21 Z_{\odot}$, distance $D = 474$ kpc): Schrubba et al. (2017) mapped CO(2–1) in four 250 pc regions using the Atacama Large Millimeter/submillimeter Array (ALMA) at 2.0 pc (FWHM) and 0.635 km s^{-1} resolutions. They found ~ 150 small CO cores with average 2.3 pc radius, 1.1 km s^{-1} linewidth, $2.7 \times 10^3 \text{ M}_{\odot}$ virial mass, and $125 \text{ M}_{\odot} \text{ pc}^{-2}$ surface density, concentrated inside $\sim 10^6 \text{ M}_{\odot}$ dust+gas complexes. The conversion factor for CO emission to total molecular mass was derived from the dust emission corrected for H I to be $\alpha_{\text{CO}} = 85 \pm 25 \text{ M}_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ in the two fields with compact H α and high CO luminosities, and it was derived to be much larger, 235 ± 72 and $572 \pm 93 \text{ M}_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ in the two fields with extended H α and low CO luminosity. For the 2.3 pc CO cores themselves, α_{CO} was within a factor of two of the Milky Way value, and the cores looked like normal Milky Way clouds: The H $_2$ densities calculated from the virial theorem, pressure balance, and excitation are all about the same, 10^3 cm^{-2} , and the extinctions through the H $_2$ envelope and CO core, 0.5 mag and 2.3 mag, are comparable with Milky Way values.
- **DDO 50** ($12 + \log \text{O}/\text{H} = 7.92$ or $0.17 Z_{\odot}$, $D = 3.27$ Mpc): Shi et al. (2016) detected CO(2–1) from two sources in DDO 50 with the IRAM 30-m telescope at a resolution of 170 pc. The emission line in one of them, DDO 50A, was detected at a signal-to-noise ratio of 5.9σ and 18 km s^{-1} FWHM; in the other, DDO 50B, there were two components with combined 6.1σ detection and 18 km s^{-1} FWHM. Using the estimated dust mass from far-infrared (FIR) emission minus the observed H I mass to determine the total molecular mass, the conversion factors were derived to be 546_{286}^{+1095} and 302_{202}^{793} in solar mass $(\text{K km s}^{-1} \text{ pc}^2)^{-1}$.
- **NGC 2366** ($12 + \log \text{O}/\text{H} = 7.89$ or $0.16 Z_{\odot}$, $D = 3.4$ Mpc): Oey et al. (2017) used the Northern Extended Millimeter Array (NOEMA) at $7.9 \text{ pc} \times 5.8 \text{ pc}$ resolution to detect 5 CO(2–1) clouds around Mrk71-A, which is a young superstar cluster of mass $1.4 \times 10^5 \text{ M}_{\odot}$ in NGC 2366. The average cloud radius is ~ 4.6 pc, and the virial mass is 10^5 M_{\odot} , making the average virial density $\sim 5,000 \text{ cm}^{-3}$ and extinction 14 mag. The average virial mass is close to the average luminous mass, $1.26 \times 10^5 \text{ M}_{\odot}$, using an assumed conversion factor of $X_{\text{CO}} = 50 \times 10^{20} \text{ H}_2 \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$. Taking the same ratio to the Milky Way values, this becomes $\alpha_{\text{CO}} = 107 \text{ M}_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$.
- **Kiso 5639** ($12 + \log \text{O}/\text{H} = 7.83$ or $0.14 Z_{\odot}$, $D = 24.5$ Mpc): Kiso 5639 is a lopsided dwarf starburst of the tadpole morphology ($M_{\text{star}} \sim 5 \times 10^7 \text{ M}_{\odot}$) with a giant star-forming region on one side, 300 pc across, and having an SFR of $\sim 0.04 \text{ M}_{\odot} \text{ year}^{-1}$. Elmegreen et al. (2018) mapped it in CO(1–0) with NOEMA at $340 \text{ pc} \times 440 \text{ pc}$ and 5.1 km s^{-1} resolutions. Assuming $\alpha_{\text{CO}} = 100 \text{ M}_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$, they derived a molecular cloud mass of $2.9 \times 10^7 \text{ M}_{\odot}$ and $\Sigma_{\text{CO}} = 120 \text{ M}_{\odot} \text{ pc}^{-2}$ with two primary components separated by 19 km s^{-1} . This internal molecular velocity spread is a large fraction of the total galaxy rotation speed, 35 km s^{-1} ,

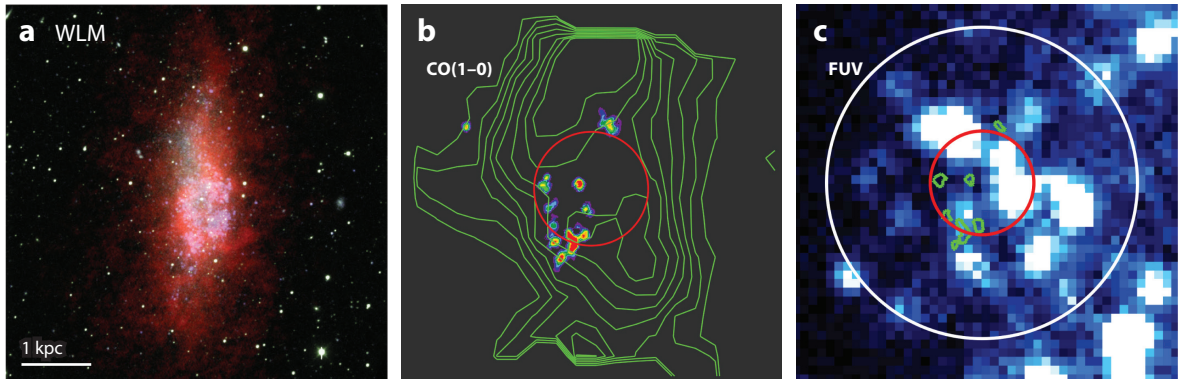


Figure 4

(a) False-color image of WLM. Blue is FUV emission, green is V -band emission, and red is atomic hydrogen gas emission. (b,c) Star-forming region in WLM at $0.13 Z_{\odot}$. The red circle has a diameter of 18 arcsec = 86 pc. (b) False-color ALMA map of CO(1–0). *Herschel* [CII] λ 158 μ m emission (green contours) defines the PDR. (c) GALEX FUV image. Small green contours outline the CO cores. We thank Lauren Hill for producing panel *a*. In panel *b*, data from Rubio et al. (2015) and Cigan et al. (2016) used with permission of the lead authors. Abbreviations: ALMA, Atacama Large Millimeter/submillimeter Array; FUV, far-ultraviolet; GALEX, *Galaxy Evolution Explorer*; PDR, photodissociation region; WLM, Wolf–Lundmark–Melotte.

suggesting a catastrophic event connected with either the formation or the destruction of the molecular cloud. The molecular cloud itself is not extraordinary aside from its large mass. Using the deconvolved radius and velocity dispersion, the virial parameter is 1.8 (less than 1.1 for each component), and the surface density corresponds to $A_V = 0.8$ mag. The pressure in the cloud is also reasonable for a starburst region, $4.8 \times 10^5 k_B$, which is like the pressure in Milky Way giant molecular clouds (GMCs).

- **DDO 53** ($12 + \log O/H = 7.82$ or $0.13 Z_{\odot}$, $D = 3.68$ Mpc): Shi et al. (2016) detected the CO(2–1) line in DDO 53 at $S/N = 7.1\sigma$ with the IRAM 30-m at 200 pc resolution. Using the estimated dust mass minus the observed H_I mass to determine the total molecular mass, they derived a conversion factor of $\alpha_{CO} = 261_{-249}^{+940} M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$.
- **WLM** ($12 + \log O/H = 7.8$ or $0.13 Z_{\odot}$, $D = 985$ kpc): Rubio et al. (2015) used ALMA to map CO(1–0) in two ~ 300 pc regions of WLM with $6.2 \text{ pc} \times 4.3 \text{ pc}$ spatial resolution (HPBW) and 0.5 km s^{-1} velocity resolution (FWHM). They found 10 small clouds with an average radius of 2.5 pc and an average virial mass of $2.8 \times 10^3 M_{\odot}$ (see **Figure 4**). The individual clouds satisfied the usual correlations for GMCs in the Milky Way (Larson 1981), namely linewidth versus size and mass versus radius, although they occupied the low-mass and low-radius ends of these correlations. The CO clouds are also approximately virialized, considering that the H₂ density required for virial equilibrium is about equal to the density required for CO excitation (i.e., $\sim 10^3 \text{ cm}^{-3}$), and this density multiplied by the square of the linewidth gives an internal pressure about equal to the cloud boundary pressure derived from the weight of the overlying gas as observed in dust emission. The extinctions in the H_I+H₂ envelope and the CO cores themselves are also about equal to the threshold extinctions for H₂ formation ($A_V = 0.3$ mag and 1.5 mag, respectively), considering the conversion of gas surface density to extinction, assuming the DGR scales with metallicity. Further study of the WLM clouds and their environments has been conducted by Archer et al. (2022), where they find no obvious environmental characteristics driving the formation of CO cores in WLM.
- **Sextans A** ($12 + \log(O/H) = 7.54$ or $0.07 Z_{\odot}$, $D = 1.4$ Mpc): A marginal detection of CO(1–0) at $S/N = 3.4\sigma$ is reported by Shi et al. (2015) in the main star-forming region of

Sextans A with the IRAM 30-m telescope at 150-pc resolution. Using the derived dust mass minus the observed HI mass, the molecular mass was determined to be $(1.0 \pm 0.3) \times 10^7 M_{\odot}$, which implies $\alpha_{\text{CO}} = (2.8 \pm 1.1) \times 10^3 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$.

- **Sextans B or DDO 70** ($12 + \log(\text{O}/\text{H}) = 7.53$ or $0.07 Z_{\odot}$, $D = 1.38$ Mpc): Shi et al. (2016) detected CO(2–1) in Sextans B at $S/N = 5.5\sigma$ with 74 pc resolution on the IRAM 30-m telescope. Using the dust mass minus the HI mass, they derived $\alpha = 6,949_{-6067}^{+23403} M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$. With ALMA, Shi et al. (2020) also mapped the CO(2–1) emission at 1.4 pc and 0.4 km s^{−1} resolutions. They found 5 clumps with radii of 1.5 to 3 pc and velocity dispersions of 0.6 to 1 km s^{−1} that satisfied the Milky Way size–linewidth relation, and they derived virial masses of 0.7×10^3 to $3 \times 10^3 M_{\odot}$. As for other low-metallicity galaxies discussed above, the extinction required to produce the CO is $A_V \sim 1$ mag, corresponding to gas mass surface densities of $756 \pm 467 M_{\odot} \text{pc}^{-2}$. At these mass column densities, Milky Way CO clumps are ~ 4 times smaller.
- **I Zw 18** ($12 + \log(\text{O}/\text{H}) = 7.18$ or $0.03 Z_{\odot}$, $D = 18.2$ Mpc): Zhou et al. (2021) tentatively detected CO(2–1) in I Zw 18 at $S/N = 3\sigma$ using NOEMA with 150 pc resolution. The total CO luminosity was found to be $\sim 4 \times 10^3 \text{ K km s}^{-1} \text{pc}^2$, which is not the lowest detected, as it was lower in two of the galaxies mentioned above (Sextans A, 3.7 ± 1.0 ; DDO 70, 0.204 ± 0.037 in units of $10^3 \text{ K km s}^{-1} \text{pc}^2$). I Zw 18 has an ~ 100 times higher SFR for its CO luminosity than these others. Normalized to the sSFR as done by Hunt et al. (2020), the ratio of the CO luminosity to the SFR is consistent with the others for its metallicity.

Among these nine dIrrs, four have been observed with a spatial resolution of several parsecs (NGC 6822, NGC 2366, WLM, Sex B), three have clear detections on spatial scales of several hundred parsecs, and two have marginal detections on these larger scales. For the high-resolution observations, the CO clouds have sizes of only a few parsecs; in three of them, the average CO cloud mass is several $\times 10^3 M_{\odot}$, and in the fourth (NGC 2366) the average mass is $\sim 10^5 M_{\odot}$. Also for the high-resolution observations, the CO cloud densities and extinctions are adequate for molecular excitation and survival, and the cloud sizes and linewidths lie close to the relationship for the Milky Way.

It is not clear from these observations how small clouds in the more quiescent dIrrs make massive stars, which must be present to explain the H α emission and the feedback that produces giant shells. Small clouds apparently also make star clusters up to several hundred solar masses, which are present in these galaxies as well. The much larger molecular mass in Kiso 5639 is presumably what allows such regions to make super star clusters and perhaps globular clusters in the early Universe.

4.1.3. Molecules in other dwarf galaxies. Dwarf galaxies with metallicities higher than that of the SMC tend to have more CO emission per unit molecular mass and cloud structure approaching that in the Milky Way, where the CO parts of most clouds have relatively small molecular envelopes and H₂ is present without CO in the denser diffuse regions (Lee et al. 2012).

In the LMC, the Columbia (Cohen et al. 1988), NANTEN (Fukui et al. 2008), and MAGMA (Hughes et al. 2010) CO(1–0) surveys at resolutions of 130 pc, 40 pc, and 8 pc cataloged 40, 272, and 175 GMCs, respectively, finding X_{CO} factors from three to six times higher than in the Milky Way using the virial theorem. The clouds have slightly narrower linewidths for their sizes than those in the Milky Way, but the mass spectrum is the normal power law (see also Brunetti & Wilson 2019). Herrera et al. (2013) measured X_{CO} more precisely by converting the dust emission into a gas mass in the N11 star-forming region and comparing that with CO luminosity and cloud virial mass. Chevance et al. (2020) mapped the FIR lines toward 30 Doradus and applied

a photodissociation region (PDR) model to determine the total molecular gas mass. They found that 75% of the molecular gas mass is not traced by CO.

Individual clouds in the LMC are not much different from Milky Way clouds. Naslim et al. (2018) used ALMA to observe clouds in the N55 region at 0.67 pc resolution and found them to be in virial equilibrium with an X_{CO} factor about twice that of the Milky Way value. Wong et al. (2019) showed that the CO linewidths in 6 LMC clouds increase with 8 μm radiation intensity and surface density for a given size. Dense gas emission from HCO^+ and HCN correlates with star formation as in other galaxies (Galametz et al. 2020, Nayana et al. 2020). In the 50 pc region around the 30 Doradus star-forming complex, Wong et al. (2022) mapped CO(2–1) and $^{13}\text{CO}(2-1)$ with ALMA at 0.4 pc resolution and found virialized clumps in filamentary structures (see also Indebetouw et al. 2013, Anderson et al. 2014). In the southern part of the molecular ridge below 30 Doradus, Finn et al. (2021) observed quiescent CO clumps and found a correlation between cloud density and the presence of young stars.

In other local dwarfs with metallicities of a few tenths solar or higher, especially in dwarf starbursts and mergers, CO is a good diagnostic for interstellar pressure and star-formation feedback. Dwarf mergers (Section 6.1) can have bright CO emission with higher localized star-formation activity than normal spirals. For example, Kepley et al. (2016) mapped CO(3–2) and CO(2–1) in the merger II Zw 40 ($0.25 Z_{\odot}$, 10 Mpc) at 24 pc resolution and found several clouds with one containing significant star formation. The clouds have higher linewidths for their sizes than Milky Way clouds, corresponding to higher gas surface densities and pressures from the merger. Consiglio et al. (2016) also mapped CO(3–2) and CO(1–0) in II Zw 40 at 20 pc resolution, and they mapped 870 μm dust emission. They found that the DGR varies with position by a factor of ~ 4 , with higher values closer to the starburst as a result of dust production by large numbers of massive stars. Gao et al. (2022) studied CO(1–0) and [C I] in the merger starburst Haro 11 ($\sim 0.27 Z_{\odot}$, 87.2 Mpc) at 460 pc resolution and measured elevated sSFRs and star-formation efficiencies in the active clumps, with values comparable with those in high-redshift galaxies and local ultraluminous infrared galaxies (ULIRGs). In the starburst Haro 2 ($0.3 Z_{\odot}$, 21 Mpc), which may not be a recent merger, Beck et al. (2020) observed CO(2–1) at 200 pc resolution and found that half the molecules are in two large clumps with embedded star formation and the other half are in an expanding X-ray bubble.

The large impact that gas accretion can have on dwarf galaxies (Section 6.2) is also evident in CO observations. Beck et al. (2018) observed He 2–10 ($0.8 Z_{\odot}$, 8.7 Mpc) in CO(3–2) with ALMA at 12 pc resolution, finding filaments that seem to be feeding the starburst and another region 25 pc in size with an outflow energy in excess of 10^{53} erg. Imara & Faesi (2019) observed the same galaxy in CO(1–0) and identified 119 virialized clouds with deconvolved sizes of ~ 26 pc and surface densities of $\sim 180 M_{\odot} \text{pc}^{-2}$, resembling Milky Way clouds but with 50% larger linewidths for their size, indicating larger pressures. Miura et al. (2018) observed the nearest starburst dwarf NGC 5253 ($Z \sim 0.3 Z_{\odot}$, 3.15 Mpc) in CO(2–1) at 3 pc resolution with ALMA. NGC 5253 is also accreting molecular gas (Miura et al. 2015). They found 118 molecular clouds with an average radius of 4.3 pc and obtained an X_{CO} factor about twice that of the Milky Way value using the virial theorem. Cloud velocity dispersions are a factor of $\sim 3\times$ larger for their size than in the Milky Way in the starburst region, and surface densities are $\sim 3\times$ higher as well, reflecting $\sim 10\times$ higher pressures from cloud gravity.

4.1.4. CO-dark gas. An important uncertainty is the atomic or molecular state of the CO-dark gas that shows up in dust emission or other tracers in the envelopes of CO clouds. It takes about 1 mag of optical dust extinction to shield molecular gas from photodissociation (Lee et al. 2018; but see Hunt et al. 2023), and for Milky Way metallicity, this magnitude corresponds to a gas

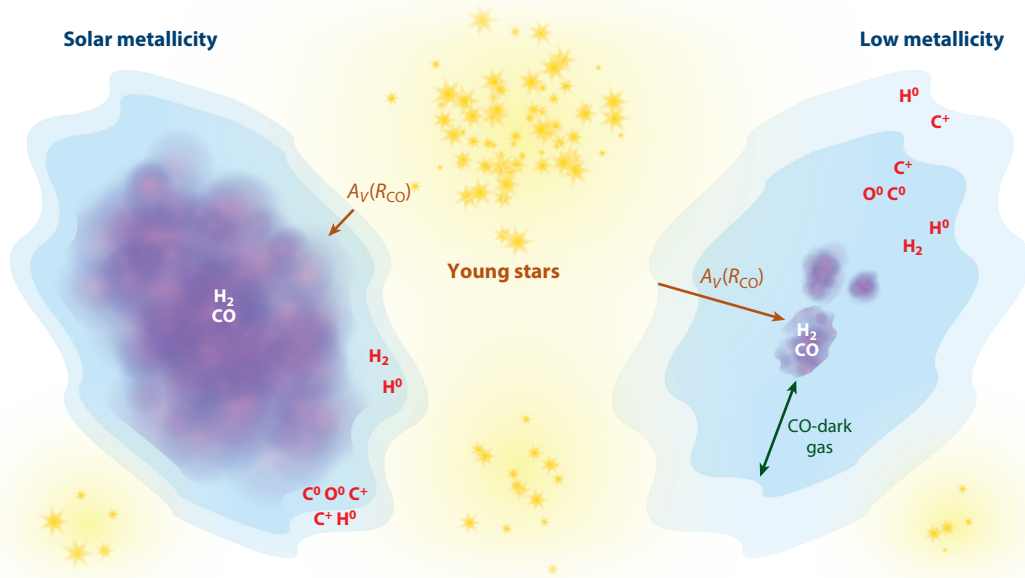


Figure 5

Sketch of the differences between a molecular cloud at solar metallicity (*left*) compared to one at low metallicity (*right*). The lower dust and metal content of dIrrs results in a greater dissociation of molecular gas and the formation of a large envelope of CO-dark gas around small CO cores. The yellow region denotes ionized hydrogen. Figure adapted from Madden et al. (2020).

surface density of $\sim 20 M_{\odot} \text{ pc}^{-2}$. At lower metallicity, the dust column for 1 mag stays constant, but the gas surface density increases, making a relatively thick PDR (Lee et al. 2015, Schruba et al. 2018) with prominent [CII] emission (Cormier et al. 2019).

For example, one can see the large PDR and tiny CO cores in WLM, a Local Group dIrr with an oxygen abundance of $0.13 Z_{\odot}$ (see **Figure 4**) (Rubio et al. 2015; see also Cormier et al. 2014). The expected reservoir of CO-dark gas at low metallicity compared to a molecular cloud at solar metallicity is sketched in **Figure 5**.

Because the envelope is not easily observed in H α , it is usually assumed to be H $_2$. However, if the mean density is low and feedback photodissociation is fast, as Hu et al. (2016, 2021) suggest in their models, or the dissociating radiation comes in through a few low-opacity sightlines (Seifried et al. 2022), then H $_2$ may not have time or opacity to form completely before it is destroyed by young stellar radiation. That would imply that much of the peripheral gas is cold H α , which is hard to detect in H α emission line profiles. Seifried et al. (2022) suggest further that the CO-rich regions also have significant amounts of cold H α , based on simulations of turbulent molecular clouds with time-dependent chemistry and radiative transfer.

H α line profiles in dwarf galaxies have been fit to cool and warm components without finding much cool H α (see Section 2.4). For example, Koch et al. (2021) suggested that optically thick (“top hat”) profiles in M31 and M33 result from multiple components and not cold H α self-absorption. In addition, there is little systematic evidence for H α self-absorption from local cold H α , i.e., surrounding molecular clouds in the Solar Neighborhood (Reach et al. 2017, Murray et al. 2018). An exception is proposed by Hayashi et al. (2019), who suggest on the basis of total gas observations through γ -ray emission that local CO-dark gas may in fact be optically thick H α . For the

LMC, the ratio of cold H I from self-absorption to total cloud mass, using $X_{\text{CO}} = 4 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ to get the cloud mass from CO, is only $\sim 10^{-3}$ (Liu et al. 2019).

Using a different method, Togi & Smith (2016) found that the H₂ excitation temperature is reasonably approximated by a power law and then NIR observations of H₂ emission, which sample only the high-excitation lines, can be extrapolated to total H₂ content. With this method applied to 5 dIrrs, they found agreement between the extrapolated H₂ and the total gas masses inferred from dust emission and SFRs, which implies the CO-dark envelopes are H₂.

Evidently, the molecular state of the CO-dark envelopes in dwarf galaxies is uncertain. Possibly, the H₂ fraction changes with spatial scale (Seifried et al. 2022), being lower for poorly resolved CO envelopes in dwarf galaxies than highly resolved CO envelopes in the local ISM. Alternatively, the H₂ formation rate could be higher than assumed in the simulations as a result of additional processes on grain surfaces (Wolfire et al. 2022) or a larger dynamic range for density.

4.2. Molecular Conversion Factor

In the Milky Way, CO is used as a tracer of the H₂ that makes up the bulk of molecular clouds. A conversion factor has been determined that, when applied to the CO measurement, gives the total molecular gas mass. Unfortunately, this conversion factor is expected to be a function of metallicity and possibly other environmental factors, and has been very hard to pin down for dwarf galaxies. Here, we discuss the methods for determining the conversion factor at low metallicity and the problems with those values.

4.2.1. Methods. As illustrated in Section 4.1.2, various strategies have been developed to quantify the reservoir of CO-dark gas. One method assumes the observed CO represents the whole cloud, and the mass is given by the virial theorem for the observed size and velocity dispersion. This virial mass is then divided by the luminosity to produce α_{CO} (Wilson 1995). This method cannot determine the envelope mass if it is not observed in CO and the envelope radius and velocity dispersion are not known. However, one might be able to assume that the CO cloud boundary pressure is determined by the weight of the overlying (invisible) envelope and derive the envelope column density from that. Contributions to the virial theorem from magnetic energy should be included too.

In another method, the dust mass in a cloud is derived from a fit of dust temperature, emissivity, and luminosity to multiband FIR observations, and then combined with a DGR previously calibrated for the appropriate metallicity from other observations. The observed cloud is presumably defined by the region of high FIR emission, so the ratio of the dust mass in this region to the DGR is the total gas mass in the cloud. Then the H I and ionized gas masses should be subtracted from the total cloud mass to determine the molecular part, which would include the CO part in the core.

There are several uncertainties with the dust mass method. The dust emissivity depends on the grain composition, size, and temperature distributions, which may vary between dense and diffuse gas, and the fit to dust mass depends on the completeness of the spectral energy distribution (SED) and the applied SED model. The DGR depends linearly on metallicity for values near the Milky Way but becomes nonlinear at low metallicity [see also Section 5.4, and Meixner et al. (2013) and Jameson et al. (2016, 2018) for issues associated with dust-based estimates of total H₂]. DGR measurements done elsewhere also have uncertainties about dark gas, and the DGR may vary from place to place in a galaxy (e.g., Hu et al. 2023).

Alternatively, one can use [C II] to infer α_{CO} . [C II] comes from PDRs in which FUV photons ionize weakly bound atoms like carbon, which has an ionization potential of 11.3 eV (Nordon & Sternberg 2016). In a typical cloud, the CO core that traces the densest H₂ is surrounded by a

PDR, which grows in size with decreasing metallicity (e.g., Bolatto et al. 2013). Early KAO observations of the [CII] $\lambda 158 \mu\text{m}$ line in IC 10 and the LMC found high $L_{[\text{CII}]} / L_{\text{CO}(1-0)}$ ratios, suggesting substantial CO-dark gas (Poglitsch et al. 1995, Madden et al. 1997, Israel & Maloney 2011). The *Herschel Space Observatory* and Stratospheric Observatory for Infrared Astronomy (SOFIA) extended these results, highlighting the diagnostic capabilities of [CII] as a tracer of CO-dark gas in the LMC, SMC (e.g., Requena-Torres et al. 2016, Jameson et al. 2018, Lebouteiller et al. 2019, Chevance et al. 2020), and NGC 4214 (Fahrion et al. 2017). With *Herschel* [CII] and ALMA CO observations of the SMC, Jameson et al. (2018) found that CO emission with the Milky Way value of α_{CO} traces only 5%–60% of the gas associated with CO; CO/[CII] increases with A_V , confirming that [CII] emission extends beyond the CO cores.

The *Herschel* Dwarf Galaxy Survey (DGS; Madden et al. 2013) observed a suite of FIR and MIR fine structure emission lines, including [CII], in 50 star-forming dwarf galaxies. These observations allowed detailed PDR and photoionization modeling (Cormier et al. 2015, 2019), setting up a strategy to quantify the total dark gas using [CII]. For example, Cormier et al. (2019) showed that the PDR covering factor increases with metallicity, and [CII] is mainly in the PDRs. Madden et al. (2020) and Ramambason et al. (2023) used this strategy to conclude that CO traces a small fraction of the star-forming gas in dwarf galaxies, whereas [CII] traces more than 70% of the total molecular gas, most of it being the CO-dark gas.

As for the dust method, there is an uncertainty with the [CII] method in that the emission can come from diffuse HI and ionized gas as well as the envelopes of CO cores (Ramambason et al. 2023). If particular clouds are to be measured, such as the clouds associated with CO, then maps of the dust or [CII] concentrations are needed to define the cloud boundaries. If the total dark gas mass is desired instead, i.e., regardless of association with CO or star formation, then the total mass from dust minus the mass of the CO cores derived from the Milky Way value of α_{CO} should give about the same result as the total mass from [CII], which is presumably not present in CO cores because of their high opacity to FUV. The [CII] method is currently used for high- z galaxies to infer the total H_2 mass (e.g., Zanella et al. 2018).

A related method is to observe carbon in all of its important forms, i.e., [C], [CII], and CO, and to use the abundance of carbon relative to hydrogen to get the total hydrogen mass. Subtracting the HI mass then gives H_2 . Pineda et al. (2017) do this for the Magellanic Clouds and find substantial amounts of H_2 without CO, and they find that in H_2 -dominant regions, most of the carbon is in the form of [CII].

4.2.2. Observations. CO-dark molecular envelopes have been observed in dust emission, [CII], and [C], and they have been inferred from the virial theorem using the size and CO linewidth in the region. For a resolved CO cloud, the mass derived by these methods divided by the CO luminosity should be similar to the α_{CO} of the Milky Way (Rubio et al. 1993a), i.e., independent of metallicity down to at least the SMC value (Bolatto et al. 2008). This similarity arises because the CO-dark envelope is mostly avoided when the CO cloud core is measured directly, and CO cores at low metallicity resemble CO clouds in the Milky Way (Section 4.1.2).

Recent observations of the increase in α_{CO} with decreasing metallicity for local dwarf galaxies are provided by Leroy et al. (2011), Schruba et al. (2012), Hunt et al. (2015, 2020, 2023), Amorín et al. (2016), Shi et al. (2016), Accurso et al. (2017), Madden et al. (2020), and Ramambason et al. (2023). Similar studies at high redshift show the same inverse relationship, although not generally to such low metallicities (Genzel et al. 2012). Of these studies, only Hunt et al. (2015, 2020), Shi et al. (2016), and Ramambason et al. (2023) apply their modeling to observations of galaxies with metallicities as low as $\sim 0.1 Z_{\odot}$. Considering the small number of such galaxies with CO detections, the scaling of $\alpha_{\text{CO}}(Z)$ is not well constrained (see review in Bolatto et al. 2013).

Using the DGS observations and single cloudy models, Madden et al. (2020) found an α_{CO} that is well correlated with metallicity and very steeply rising toward low Z . Also using the DGS data but with a statistical Bayesian framework to account for the structure of the unresolved gas with multiple components and a clumpy distribution of CO, Ramambason et al. (2023) found a wide scatter of α_{CO} that is correlated with CO clumpiness also. A steep relationship for $\alpha_{\text{CO}}(Z)$ corresponds to a more diffuse CO source, whereas a flatter relationship found for some dwarf galaxies corresponds to more clumpy CO structures.

Submillimeter transitions of [C I] have also been used as tracers of CO-dark gas in observations as well as theory and simulations (e.g., Papadopoulos et al. 2004, Offner et al. 2014, Li et al. 2018, Jiao et al. 2019). Glover & Clark (2016), Heintz & Watson (2020), and Ramambason et al. (2023) show that [C I] is an excellent tracer of total M_{H_2} in their models and that the conversion factor depends on metallicity approximately as Z^{-1} .

4.2.3. Theory. Theoretical discussions and models of $\alpha_{\text{CO}}(Z)$ by Wolfire et al. (2010) and Krumholz et al. (2011) consider uniform spherical clouds with dust extinction and grain-surface formation of H_2 to derive an envelope opacity, and from this the CO-to- H_2 ratio. The resulting fractional abundance of CO depends on the fractional abundance of H_2 . The strongest scaling with metallicity is through an A_V term, because $\alpha_{\text{CO}} \propto \exp(2.12/A_V)$ in their model for $A_V \propto Z$. A magnetohydrodynamical simulation of H_2 and CO formation by Glover & Mac Low (2011) finds a comparably strong scaling of $\alpha_{\text{CO}} \propto A_V^{-3.5}$ down to $Z/Z_\odot = 0.03$. These results agree with observations by Hunt et al. (2015) down to $Z/Z_\odot = 0.1$ but appear too steep below that. Additional hydrodynamic simulations are discussed by Shetty et al. (2011); a recent detailed nonequilibrium chemical model of the ISM is provided by Katz (2022).

Bialy & Sternberg (2015) determined the relative abundances of H_2 , CO, and other important molecules from a detailed chemical network. Bialy & Sternberg (2016) then examined dust opacity at the molecular transition, which is where the rate of H_2 formation, typically on dust, balances the H_2 photodissociation rate in the Lyman–Werner bands. Because the radiation field is attenuated by both H_2 photodissociation and dust, metallicity plays a role in determining the fraction of the incident photons that dissociate H_2 . The mass surface density of the shielding layer has an additional dependence on the inverse of metallicity from the DGR, making the HI envelopes of the H_2 regions even more massive at lower metallicity. Schrubba et al. (2018) found good agreement between these models and observations of HI in metal-poor galaxies.

Hu et al. (2016) modeled cold and warm HI and cold H_2 in a whole dwarf galaxy with metallicity $Z/Z_\odot = 0.1$. They found large H_2 fractions, 25% to 70%, in diffuse (non-star-forming) gas for the models with feedback, and small H_2 fractions for these models in the star-forming gas, defined to be where the density exceeds 100 cm^{-3} . The cold gas lies 3 to 10 times closer to the midplane than the warm gas because of its higher density and radiative shielding closer to the plane. Much of the gas with density $> 100 \text{ cm}^{-3}$ is cold HI because feedback disrupts the H_2 in their models. In further studies, Hu et al. (2021) simulated the ISM with star formation in collapsing clouds for a galaxy patch 1 kpc square and 10 kpc high using metallicities ranging from 0.1 to $3 Z_\odot$. They found that the SFR is independent of metallicity, and, like their previous result, the H_2 is often out of equilibrium and at low relative abundance because of its long formation time. CO is less affected by the low H_2 abundance, however, making the H_2 -to-CO ratio low in the cloud envelopes. Whereas the H_2 fraction was high in the CO regions, it decreased to low values, < 0.1 , in the CO-free molecular cloud periphery. At $Z/Z_\odot = 0.1$, more than 40% of the H_2 was in peripheral cloud gas with minimal CO and an H_2 fraction less than 10%. Hu et al. (2022) discussed these results explicitly in terms of the X_{CO} factor: On large scales surrounding CO cores, molecular H_2 exists but with lower X_{CO} than calculated from equilibrium models, and on the small scale of the CO

region, dust opacity is high enough to make the H_2 fraction high regardless of metallicity, and then X_{CO} approaches the Milky Way value.

Hirashita & Harada (2017) and Hu et al. (2023) calculated $X_{\text{CO}}(Z)$ for various metallicities, including dust evolution in the DGR. Whereas Hu et al. continue to model nonequilibrium chemistry, Hirashita & Harada note that the H_2 formation time can be less than the free fall time for densities exceeding $\sim 10^3 \text{ cm}^{-3}$, and thus H_2 is assumed to reach equilibrium in their models. This difference arises because the formation time scales inversely with density for a given DGR, being a collisional process, whereas the free fall time scales inversely with the square root of density, driven by self-gravity. Both studies conclude that molecule formation can be enhanced in local regions of high DGR, which may arise through dust growth or dust formation in supernovae and evolved stars. Hirashita & Harada (2017) use the chemistry from Glover & Mac Low (2011) modified for a different dust abundance and grain size distribution that was calculated explicitly and found good agreement with the observed $\alpha_{\text{CO}}(Z)$ down to 20% solar abundance. Hu et al. (2023) also calculated dust evolution but with a time-dependent chemistry in a hydrodynamic model of a WLM-like dwarf galaxy with 10% solar abundance. Hu et al. found that dust growth in dense gas is required to reproduce the observed CO luminosity at the observed SFR; otherwise, UV radiation from star formation will destroy the CO clouds. Thus, the DGR is higher in CO clouds than in proportion to the overall metallicity. Hu et al. continued to get a low H_2 fraction because of its slow formation, and so essentially found no CO-dark molecular gas, which made α_{CO} comparable with that in the Milky Way.

Accurso et al. (2017) and Hunt et al. (2020) make the point that α_{CO} depends on both the sSFR—through variations in the molecular depletion time, τ_{d} —and the metallicity, which is partly determined by molecular photodissociation in interclump gas shielded to various degrees by dust (Israel 1997). Higher sSFR leads to lower τ_{d} (Huang & Kauffmann 2014), although there is no strong correlation for local galaxies according to Jameson et al. (2016), and lower L'_{CO}/SFR , at solar and higher metallicity, when molecular clouds are presumably saturated with CO. Here, L'_{CO} refers to a measurement in observational units, $\text{K km s}^{-1} \text{ pc}^2$ rather than L_{\odot} .

4.3. Molecular Gas in Tidal Dwarfs and Stripped Tails

Tidal dwarf galaxies (TDGs) form as self-gravitating debris of gas and stars in tidal tails (see review in Duc & Renaud 2013). Because the gas comes from a larger galaxy, it has the higher metallicity of the larger galaxy and, therefore, a high metallicity for its mass. As a result, CO is easier to detect in TDGs than in dIrrs of similar mass.

The CO luminous and virial masses in a TDG that appears to have been stripped off of NGC 3077 from an interaction with M81 exceed $10^7 M_{\odot}$ in each of three complexes; the CO exists beyond where the HI column density peaks at $1.5 \times 10^{21} \text{ cm}^{-2}$ (Heithausen & Walter 2000). This peak exceeds the HI to H_2 threshold in the Solar Neighborhood, where it is $\sim 5 \times 10^{20} \text{ cm}^{-2}$ (Savage et al. 1977; however, see Seifried et al. 2022).

Braine et al. (2001) discovered CO emission centered on the HI peaks in 8 TDGs and noted that the CO luminosities are $\sim 100\times$ higher than in dIrrs at the same stellar luminosities because of the $\sim 1/3 Z_{\odot}$ metallicities in the TDGs. In the TDG near NGC 3077, the SFR is low for the molecular mass, but in the TDGs studied by Braine et al. (2001), it is about the same as that in the Milky Way. Brinks et al. (2004) observed HI and CO at 750 pc resolution in the TDG near Arp 245 and concluded it is gravitationally bound.

CO has been observed in many other TDGs as well: in the intergalactic region of Stephan's Quintet and VCC 2062 (Lisenfeld et al. 2016, and references therein), near VV 114 (Saito et al. 2015), near M82 (Pasha et al. 2021), and in tidal clumps in the Leo ring (Corbelli et al. 2023).

ALMA observations of Arp 94 resolved 111 CO(2–1) clouds in the TDG down to 45 pc resolution with a mass spectrum similar to that in the Milky Way (Querejeta et al. 2021, and references therein); the molecular fraction is high ($\sim 50\%$) and the cloud velocity dispersion is higher for a given cloud mass than in the Milky Way, although the CO clouds look fairly normal.

Ram-pressure swept tails of galaxies may contain CO also, as in ESO137-001, where “fireballs” aligned with the tail could have formed molecules in situ (Jáchym et al. 2019). The isolated intracluster cloud in Abel 1367, which may be the remnant of a tidal tail, contains over $10^8 M_{\odot}$ of molecules, mostly not star-forming (Jáchym et al. 2022).

5. DUST AND METALLICITY

One of the most prominent characteristics of dwarf galaxies is their low abundance of metals and dust. Metals originate in stars, with dust forming in novae and supernovae (Haenecour et al. 2019, Hoppe et al. 2022), in the expanding atmospheres of evolved stars (see the review Dwek 2005), and more generally in the denser regions of the ISM. Dust is important for interstellar molecules, as it is the primary site for H_2 formation while shielding molecular clouds from photodissociative radiation (Bialy & Sternberg 2015).

There is spectroscopic evidence that the composition of dust in dwarf galaxies is made up of the main Galactic dust components, silicates (e.g., Thuan et al. 1999, Jones et al. 2023), i.e., carbonaceous dust including polycyclic aromatic hydrocarbons (PAHs) (Section 5.2) (e.g., Madden et al. 2006). Although the proportion and size distribution of these components differ (e.g., Zubko et al. 2004, Jones et al. 2017, Hensley & Draine 2023), we can reasonably use Milky Way dust models to study low-metallicity galaxies. Dust properties depend on gas density and proximity to radiation, which determine the rate of condensation and sublimation at the surface, and on dynamical processes such as shocks, which can sputter or shatter the grains in collisions (see the review Galliano et al. 2021).

The chemical elements we measure in a galaxy today serve as a history of the evolution of its stellar populations, which, through the process of nucleosynthesis, are the sources of the elements that are injected into the ISM and cycled through successive generations. The chemical history of dwarf galaxies is also linked to the history of accretion (Section 6.2) and outflow (Section 2.2.2; see, e.g., McCormick et al. 2018). Metallicity increases with stellar mass approximately as $M_{\text{star}}^{0.3}$ near $M_{\text{star}} \sim 10^{10} M_{\odot}$ with a shallower slope for more massive galaxies (Kewley & Ellison 2008, Kirby et al. 2013). The reasons for this increase include a greater resistance to gas escape (Tremonti et al. 2004) and a higher efficiency of star formation (Calura et al. 2009) at higher galaxy mass. As stars produce metals, the relationship evolves over time (Torrey et al. 2019); for dwarfs, metallicity increases by up to 0.1 dex at constant mass from $z = 3$ to 2 (Li et al. 2022).

5.1. Heavy Elements in the Gas and Dusty Phases

Although many techniques exist to estimate the metallicity of galaxies (see the review Maiolino & Mannucci 2019, and references within), most of the metallicities of gas-rich dwarf galaxies in the local Universe and out to moderate redshifts have been measured in the ionized gas phase, frequently via the oxygen nebular lines [expressed as $12 + \log(O/H)$] (e.g., Skillman et al. 1989, Izotov & Thuan 2000, Kunth & Östlin 2000). Oxygen is one of the most abundant heavy elements. The “direct” metallicity method measures the strong optical [O III] lines ($\lambda 4363/\lambda 5007$) and compares these with calibrations based on lines that are sensitive to electron temperature (e.g., Pettini & Pagel 2004). Oxygen is the standard against which the abundances of other elements (Fe, C, and N in H II regions) are compared (Pagel 2003), which are all mainly produced in massive stars. The H abundances in the O/H ratio are determined often by optical hydrogen recombination

lines. Studying the elemental abundance ratios and how the patterns vary as a function of the metallicity in dwarf galaxies can provide a window into the chemical evolution of early galaxy environments.

Understanding the origin of N and the N/O ratio in dwarf galaxies has been a persistent problem. At low metallicities, N/O is observed to be relatively constant with Z but often with a wide scatter (e.g., Kobulnicky & Skillman 1996, Izotov & Thuan 1999, Pilyugin et al. 2003, Spite et al. 2005, López-Sánchez & Esteban 2010, Roy et al. 2021), and with some evidence for an increase of N/O in extremely low- Z galaxies (e.g., Guseva et al. 2011). Although O is a primary element (synthesized from the initial stellar hydrogen and helium), the chemical origin of N, and whether it is a primary or secondary element (production in previous stellar generations) at low Z , has been challenging to model. Preference exists for primary N production in metal-poor stars (e.g., Spite et al. 2005, Roy et al. 2021). High-mass stars are the dominant producers of oxygen. Nitrogen in dwarf galaxies has been attributed to production in massive stars (e.g., Izotov & Thuan 1999), whereas other studies suggest low- to intermediate-mass stars (e.g., Skillman et al. 1998, Henry et al. 2000, Spite et al. 2005). Recent models by Roy et al. (2021) suggest that dwarf galaxies retain their massive stellar winds, thus producing the observed N/O versus O/H relation, and that retention of supernova ejecta is not likely to account for the observed N/O until higher metallicities are reached and AGB stars contribute secondary N.

The Extremely Metal-Poor Representatives Explored by the Subaru Survey (EMPRESS) of extremely metal-poor galaxies (about 2% Z_{\odot}) measured abundances of Ne/O and Ar/O to be comparable with those of other local dwarf galaxies with lower than expected N/O (Kojima et al. 2021), consistent with findings by Guseva et al. (2011). However, in contrast, the Fe/O is excessively high: 90% Z_{\odot} to 140% Z_{\odot} is proposed by Kojima et al. (2021) to originate from supermassive stars, whereas Guseva et al. (2011) show a prominent decrease in Fe/O as metallicity increases, which is likely due to the depletion of Fe onto dust grains.

Metallicity variations measured in the gas phase across dwarf galaxies are, for the most part, negligible (e.g., Kobulnicky & Skillman 1996, Croxall et al. 2009), unlike the metallicity gradients across large star-forming disk galaxies (e.g., Sanders et al. 2012). Some elemental abundances in the neutral H I gas of I Zw 18, one of the most metal-poor galaxies in the local Universe, were observed with UV absorption lines to be lower ($\sim 1/46 Z_{\odot}$) than those in H II regions ($\sim 1/31 Z_{\odot}$), measured with the commonly used optical lines (Aloisi et al. 2003, Lebouteiller et al. 2013). One explanation surmises the infall of more metal-poor gas mixing with the outer H I. Cosmological simulations of dwarf galaxies have explained the uniformity of metallicity as the result of turbulent diffusion (e.g., Williamson et al. 2016, Escala et al. 2018). However, simulations following the chemical evolution of each enrichment event for individual elements indicate that metal mixing is not uniform across a species (Emerick et al. 2018).

The depletion of elements from the gas phase to dust modifies the relative gas-phase elemental abundances and makes it challenging to get an accurate assessment of them (e.g., Jenkins 2009, Tchernyshyov et al. 2015, De Cia et al. 2016, Roman-Duval et al. 2021, and references therein). Depletion tells us more about the dust properties. Elemental depletion patterns of the LMC ($Z = 0.5 Z_{\odot}$) and SMC ($Z = 0.2 Z_{\odot}$) have been determined from UV absorption measurements of metal ions and analyzed along with stellar abundances in studies by Tchernyshyov et al. (2015), Jenkins & Wallerstein (2017), Roman-Duval et al. (2022), and Konstantopoulou et al. (2022). Although gas-phase abundances vary throughout the galaxies, depletion patterns are not very different from those of the Milky Way. As a result, dust properties in the LMC are similar to abundance-scaled dust properties in the Milky Way, unlike those in the SMC, which does not scale similarly to the Milky Way but has wider variations (see comparison of abundances and depletions in the LMC, SMC, and Milky Way in Galliano et al. 2018). Depletion studies show that

though star-formation histories can differ widely in galaxies, the origin of dust in low-metallicity galaxies and more metal-rich galaxies is similar (e.g., Konstantopoulou et al. 2022).

5.2. Dust Properties of Dwarf Galaxies

The dust properties of galaxies, such as the dust mass relative to gas and the distributions of temperature, composition, and size, can be extracted from models of the dust SEDs. The specific dust characteristics depend on the approach adopted for the macrophysics of the SED modeling (e.g., the radiative transfer), and the microphysics in the dust models (composition). Modified blackbody (MBB) models, assuming a single dust temperature, T_{dust} , are often used to interpret the observed SEDs of the dust emission. These models relate T_{dust} to the dust mass and the dust emissivity index, β , which is dependent on the dust composition. The MBB models, though conveniently simple, are found to produce lower dust masses (e.g., Dale et al. 2012, Rémy-Ruyer et al. 2013) than more physically realistic models (e.g., Dale et al. 2012, Rémy-Ruyer et al. 2015, Galliano 2018, Hunt et al. 2019, Aniano et al. 2020), which assume a starlight intensity distribution. With a distribution of radiation fields as is the case in galaxies (hence of equilibrium grain temperatures), application of an MBB results in a β that is artificially decreased to compensate for the broadening of the SED, which leads to a higher fitted temperature, and thus to a lower dust mass (see Galliano et al. 2018, and references therein for a detailed discussion of the phenomenology of SED modeling and dust models).

Infrared Astronomical Satellite brought us the first 12 to 100 μm view of the global dust properties of dwarf galaxies, highlighting the trend of warmer overall temperatures compared to massive spirals, as determined by the 60 μm /100 μm ratio. These higher temperatures resulted in lower inferred DGRs (e.g., Melisse & Israel 1994, Hunter et al. 2001b, and references therein). Early spectroscopic observations of NGC 5253 and II Zw 40 also revealed an absence of PAHs (Roche et al. 1991), which are carbonaceous dust grains with prominent MIR emission features. In contrast, PAHs are pervasive in star-forming disk galaxies containing PDRs (Tielens 2008, and references therein). With greater sensitivity, higher spatial resolution, and more MIR to FIR wavelength coverage in larger samples of dwarf galaxies, *Infrared Space Observatory* and then the *Spitzer Space Telescope* confirmed these characteristics of low-metallicity galaxies and established more clearly the paucity of PAHs in dwarf galaxies (Reach et al. 2000; Houck et al. 2004; Engelbracht et al. 2005; Galliano et al. 2005, 2008; Madden et al. 2006; Draine & Li 2007; Hunter & Kaufman 2007; Rosenberg et al. 2008; Hunt et al. 2010; Sandstrom et al. 2010; Chastenet et al. 2019; Aniano et al. 2020). As PAHs are suggested to be the main carriers of the 2175 Å UV bump in the dust extinction curve (Fitzpatrick 1986, Mathis 1994, Misselt et al. 1999, Li & Draine 2001), the LMC, with its relatively low PAH abundance, shows a lower 2175 Å bump than the Milky Way, and the SMC, with fewer PAHs than the LMC, has an even lower 2175 Å feature (e.g., Prevot et al. 1984, Fitzpatrick 1986, Gordon & Clayton 1998, Weingartner & Draine 2001, Li & Draine 2002, Draine 2003, Gordon et al. 2003, Fitzpatrick & Massa 2007, Hirashita & Murga 2020).

High spatial-resolution FIR-to-submillimeter observations arrived with *Herschel*, thus going beyond the FIR peak into submillimeter wavelengths, where the total dust mass can be more accurately quantified. *Herschel* carried out the DGS (Madden et al. 2013), observing 50 dwarf galaxies with a wide range of metallicities, including 2 galaxies that are among the most metal poor in the local Universe, I Zw 18 ($0.05 Z_{\odot}$) and SBS0335-052 ($0.03 Z_{\odot}$). Comparison of these dwarf galaxies with the more metal-rich sample from the *Herschel* KINGFISH (Key Insights on Nearby Galaxies: a Far-Infrared Survey with *Herschel*) survey (Kennicutt et al. 2011; Dale et al. 2012, 2017), and subsequently the DustPedia survey (e.g., Galliano et al. 2021), provided a broad range of environments and star-formation activities to help us understand how dust properties

evolve as galaxies become enriched over almost 2 dex in metallicity (Rémy-Ruyer et al. 2013, 2015; Galliano et al. 2021).

Compared to their gas and stellar masses, the dust masses in dwarf galaxies are lower than those of more metal-rich galaxies. Stellar feedback in dwarf galaxies carves out ISM channels (e.g., Emerick et al. 2019), making more porous ISM structures (Section 2.2.2), as also evidenced by high galaxy-wide L_{FIR} and harder radiation field revealed by the presence of high-energy fine structure lines emitting in the MIR and FIR bands (e.g., Cormier et al. 2015). Consequently, combined with the smaller grain size distribution, the overall dust temperatures in dwarf galaxies are warmer, as evidenced by their dust SEDs peaking at shorter wavelengths, often between ~ 40 to $60 \mu\text{m}$, compared to $100 \mu\text{m}$ and beyond for dustier galaxies (e.g., Hirashita et al. 2008, Rémy-Ruyer et al. 2013, Galliano et al. 2021). Overall, dwarf galaxies show broader profiles around the peaks of their SEDs (Rémy-Ruyer et al. 2015), reflecting a wider temperature distribution for the grains.

5.3. Low Metallicity and Dust Size Effects

SED modeling suggests that the dust size distributions in dwarf galaxies can shift to smaller sizes compared to more metal-rich galaxies (e.g., Galliano et al. 2005), although degeneracies exist in the SED approach. The SMC extinction curve also suggests a shift to smaller sizes (e.g., Cartledge et al. 2005). At extremely low metallicities (e.g., I Zw 18), theoretical models by Hirashita et al. (2020) predict large grains ($\sim 1 \mu\text{m}$) as the mass is dominated by grains formed in supernova ejecta. At more moderate metallicity (e.g., SMC), grains are shattered via shocks and become smaller, down to a few nanometers (e.g., Jones 2004, Slavin et al. 2020, Priestley et al. 2022), whereas at higher metallicity they can become larger as they accrete gas-phase species in the ISM. The dust size distribution, biased toward smaller grains, tends to increase the dust temperature distribution. The predicted increase of the silicate-to-carbon dust ratio via shock processing and differing production timescales contribute to the characteristically different extinction properties and dust SEDs observed in dwarf galaxies. The evolution of the dust size distribution can also affect the metallicity dependence of the CO-to-H₂ conversion factor (Section 4.2; Hirashita 2023).

PAHs are often associated with UV-illuminated edges of PDRs around massive stars. The lower abundance of PAHs in dwarf galaxies can therefore be a consequence of low filling factors for PDRs (see Section 4.1.4). By contrast, the low abundance of PAHs can be attributed to lower dust shielding, encouraging PAH destruction from hard radiation environments (e.g., Madden et al. 2006, Hunt et al. 2010) and supernova shocks (e.g., O'Halloran et al. 2006, Micelotta et al. 2010). An example of these combined effects observed in the SEDs of star-forming dwarf galaxies is SBS0335-052, which is one of the lowest-metallicity galaxies in the local Universe ($\sim 1/40 Z_{\odot}$). SBS0335-052 has MIR silicate absorption features on a continuum without PAH features, and an SED peaking at $\sim 30 \mu\text{m}$, which is an unusually short wavelength for the FIR peak, indicating very warm dust (Thuan et al. 1999, Houck et al. 2004).

The fraction of total dust mass in the form of PAHs correlates with metallicity at $12 + \log \text{O}/\text{H} < 8.0$ (e.g., Draine et al. 2007, Rémy-Ruyer et al. 2015, Aniano et al. 2020). With a sample of ~ 800 galaxies, Galliano et al. (2021) found this correlation to be striking over 2 dex in metallicities and also found a weaker anticorrelation with the radiation field. The anticorrelation may be related to the destruction of PAHs via photoprocessing in the hard radiation field of the diffuse ISM, which also goes hand in hand with the overall warmer dust and the presence of very small grains (of a few nanometers) emitting in the MIR continuum (e.g., Madden et al. 2006, Rosenberg et al. 2008, Hunt et al. 2010, Sandstrom et al. 2010, Chastenot et al. 2019, Aniano et al. 2020, Hirashita et al. 2020, Galliano et al. 2021). For example, Sandstrom et al. (2010) and Chastenot et al. (2019) proposed that in the Magellanic Clouds molecular clouds are the sites

where PAHs form before photoprocessing in the diffuse ISM. Another PAH evolution scenario has them being produced by the shattering of large carbon grains (Seok et al. 2014). Furthermore, PAHs may not yet have been produced in the lowest-metallicity galaxies due to a delayed production of carbon stardust (Dwek 2005, Galliano et al. 2008).

5.4. Dust-to-Gas Mass Ratios

Measurements of the DGR in galaxies over a wide range of metallicities give us some insight into how dust may have evolved from early, metal-poor galaxies into metal-rich galaxies, such as our Milky Way. Interpretation requires a dust evolution model, dust and gas mass measurements, and metallicity measurements. Although the number of very low-metallicity dwarf galaxies with measured dust masses is rather limited owing to telescope sensitivity issues (e.g., SBS0335-052; Hunt et al. 2014, Rémy-Ruyer et al. 2015, Cormier et al. 2017), the DGR has been measured in galaxies with metallicities covering almost two orders of magnitude (e.g., Rémy-Ruyer et al. 2015, De Vis et al. 2019, Cigan et al. 2021, Galliano et al. 2021).

Figure 6 demonstrates the behavior of the DGR as a function of metallicity. At very low metallicities, $12 + \log(\text{O}/\text{H})$ less than 7.9 (Z less than $0.2 Z_{\odot}$), condensation dust in supernova ejecta appears to be the dominant production process, but it has a low efficiency (e.g., Asano et al. 2013a, De Vis et al. 2017, Galliano et al. 2021). Dust is a very meager component of the ISM at the lowest metallicities—low compared to the already low metal abundances in these galaxies, and lower still compared to the gas in star-forming metal-rich galaxies. As the buildup of dust progresses, the growth of grains via accretion of metals from the gas phase takes place in the ISM (e.g., Asano et al. 2013a, Zhukovska 2014, Zhukovska et al. 2016), and the DGR begins an abrupt rise by about two orders of magnitude between $12 + \log(\text{O}/\text{H}) \sim 7.9$ and 8.2. Above this “critical metallicity,” nonlinear regime (Asano et al. 2013a), an approximate proportionality of DGR with metallicity is observed, albeit with scatter attributed to different star-formation histories and different grain formation and destruction processes (e.g., Galliano et al. 2008, 2021; Rémy-Ruyer et al. 2014; De Vis et al. 2019; Cigan et al. 2021).

5.5. Submillimeter Excess

Beyond the FIR peak of galaxy SEDs, the observed submillimeter emission is sometimes seen as an excess that is not explained by a combination of state-of-the-art SED models, synchrotron and free-free continua, molecular lines, and cosmic microwave background fluctuations. This excess was first reported in the Milky Way by Reach et al. (1995) and shown to be present in some dwarf galaxies (e.g., Lisenfeld et al. 2002; Galliano et al. 2005, 2011; Galametz et al. 2009, 2011; Bot et al. 2010; Dale et al. 2012; Chang et al. 2021) as well as in solar-metallicity galaxies (e.g., Kirkpatrick et al. 2013). *Herschel* observations brought more attention to this excess, which seems to begin around $500 \mu\text{m}$. The presence of the excess is model dependent, showing up most often with MBB SED models (e.g., Rémy-Ruyer et al. 2013, Hermelo et al. 2016, Chang et al. 2021, Relaño et al. 2022), but also in full state-of-the-art SED models (e.g., Galliano et al. 2018, and references within).

The origin of this excess remains an open issue. One suggestion has been a very cold dust component ($T \sim 10 \text{ K}$), which implies a large dust mass and significant dust shielding to maintain the low temperature, which is unrealistic unless the cold dust existed in dense clumps (Lisenfeld et al. 2002, Galliano et al. 2005, Cormier et al. 2017). For some cases, grain emissivity variations with temperature can explain the submillimeter excess (Meny et al. 2007, Demyk et al. 2022) or magnetic grains, which seem to explain the excess in the SMC (Bot et al. 2010, Draine & Hensley 2012). Spinning grains have also been proposed (Draine & Lazarian 1998,

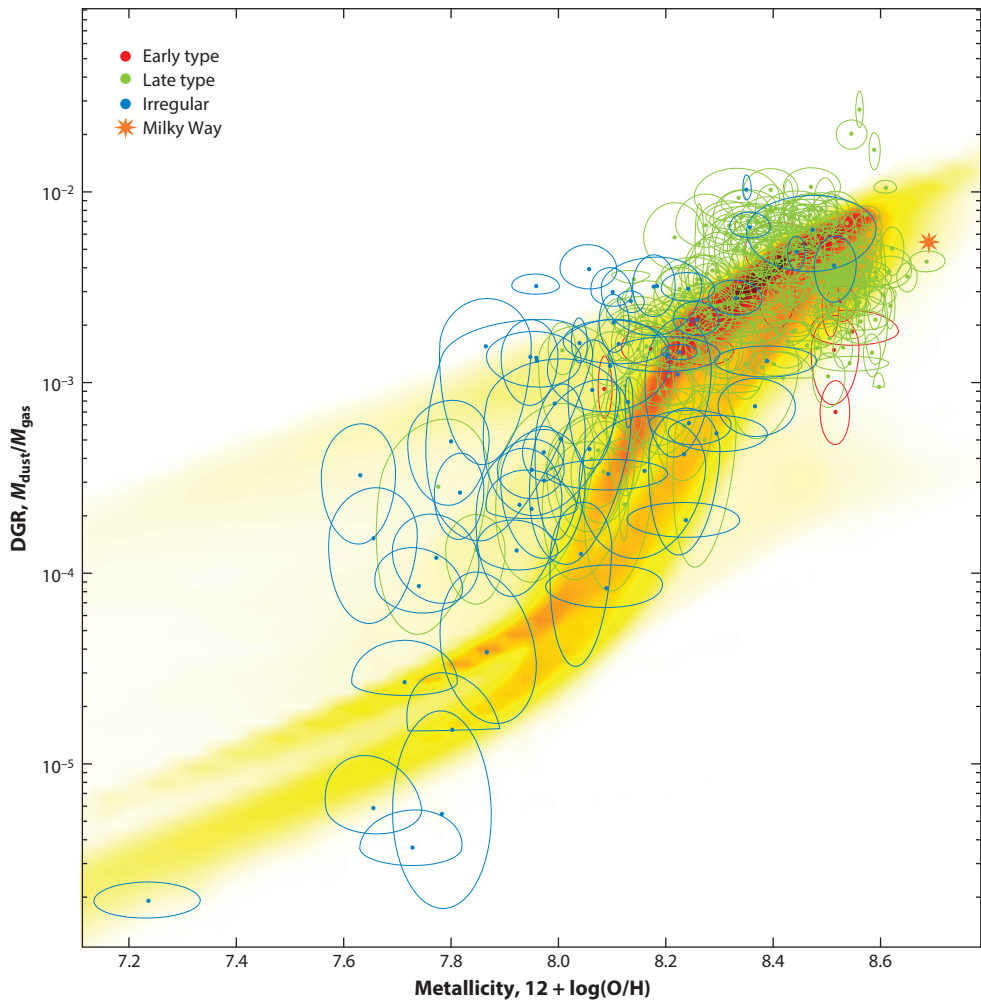


Figure 6

DGR as a function of galaxy oxygen abundance, fitted with the dust evolution model of Galliano et al. (2021). The skewed uncertainty ellipses are from the SED fitting of the DustPedia plus DGS galaxy samples. The data are color-coded in the legend according to galaxy type. The Milky Way is represented by an orange star. The posterior probability distribution of the dust evolution model is shown as a spread in yellow-orange density. For reference, solar oxygen abundance is $12 + \log(\text{O}/\text{H}) = 8.69$ (Asplund et al. 2009). Figure adapted from Galliano et al. (2021). Abbreviations: DGR, dust-to-gas mass ratio; DGS, Dwarf Galaxy Survey; SED, spectral energy distribution.

Bot et al. 2010, Draine & Hensley 2012) as a contribution to the millimeter and submillimeter emission (see the review Dickinson et al. 2018), but cannot alone explain the submillimeter excess. Bot et al. (2010) suggested that spinning grains should be combined with a temperature-dependent emissivity to explain the excess in the SMC. In the moderately low-metallicity galaxies LMC and M33, the submillimeter excess is shown to prefer the more diffuse ISM, rather than the molecular component (Galliano et al. 2011, Hermelo et al. 2016, Relaño et al. 2022). Until more sensitive telescopes can survey a statistically significant number of metal-poor galaxies in well-resolved FIR–millimeter continuum bands, the submillimeter excess remains an outstanding question.

5.6. Dust Evolution: The Story Told by the Dwarf Galaxies

To understand the evolution of dust in galaxies throughout cosmic times, it is necessary to understand the metal-enrichment processes from the lowest-metallicity primeval galaxies to more chemically evolved galaxies, which are already rich in metals. Nailing down the dust properties in dwarf galaxies is essential to form a complete picture of how the buildup of dust transpires in galaxies. The diversity of local Universe dwarf galaxies with varying metal abundances can be thought of as laboratories providing individual snapshots of different metal-enrichment stages that, taken together as an ensemble, can help to construct comprehensive self-consistent dust evolution models. Most dust evolution models since that of Dwek & Scalo (1980) are usually one-zone models following the global content of dust, metals, gas, and stars as a function of time (e.g., Dwek 1998, Asano et al. 2013a, Zhukovska et al. 2016, De Vis et al. 2017, De Looze et al. 2020, Hirashita et al. 2020, Nanni et al. 2020, Triani et al. 2020, Galliano et al. 2021), but not all models are constrained by observations of the very low-metallicity galaxies. Dust formation and destruction models attempting to reproduce the observed dust mass and predict the extinction curve should assume or model a dust size distribution as a function of time (e.g., Asano et al. 2013b, 2014; McKinnon et al. 2018; Hirashita & Murga 2020; Makiya & Hirashita 2022).

Galliano et al. (2021) perform a hierarchical Bayesian fit of a one-zone dust evolution model to the observed stellar mass, gas mass, dust mass, metallicities, and SFRs of 556 galaxies of a wide range of galaxy types (**Figure 6**). Their model reproduces the “critical metallicity” threshold above which grains begin to accrete metals and dust grows efficiently, thereby enriching the ISM. The very low-metallicity galaxies of the sample (lower than $Z = 0.2 Z_{\odot}$) are critical to constrain the full dust evolution model especially in the regime in which dust production is dominated by SN II condensation. Although most studies agree on the process of dust evolution at the lowest metallicities, some scenarios for the enrichment of the higher-metallicity galaxies have supernovae as the net dust producers (e.g., De Looze et al. 2020, Nanni et al. 2020). Spatially resolved studies would help to improve on the existing degeneracies in dust evolution models, but will be challenging for the lowest-metallicity galaxies, especially at FIR wavelengths.

6. ENVIRONMENTAL EFFECTS

Mergers, interactions, and gas accretion can change dIrrs from quiescent, with generally low surface brightness and small star-forming regions that produce low-mass clusters, into highly active, with dense molecular clouds, high sSFRs, and massive young star clusters that produce giant shells and possibly blow out into the halo. The fraction of dIrrs that are recent mergers or current accretion sites is uncertain, but there are clear examples of each as determined using several types of evidence. A few examples are reviewed here.

6.1. Mergers

Mergers and accretion are important for galaxy growth at high redshift, and these processes are still present in dIrrs today, although with reduced frequency. Zhang et al. (2020) present observations of giant stellar shells surrounding the BCD galaxy VCC 848. Computer simulations show how shells like this are evidence for a merger of two smaller galaxies, which in the case of VCC 848 started around 1 Gyr ago. Starbursts accompanied this merger, as seen in the age distribution of massive star clusters. Paudel et al. (2017) previously found old stellar shells indicative of mergers in three Virgo cluster early-type dwarfs, and Chhatkuli et al. (2023) studied 6 BCDs with giant stellar shells. Other types of evidence for mergers are halo stellar streams, as seen in And II by Amorisco et al. (2014); extended stellar halos, as seen in Tucana II by Chiti et al. (2021); steep or unusual metallicity gradients (van Zee et al. 1998, Grossi et al. 2020, Taibi et al. 2022); nonplanar

inner and outer disks, as in Ark 18 (Egorova et al. 2021); off-center black holes (Reines et al. 2020, Bellovary et al. 2021); and double AGNs (Mičić et al. 2023). The dwarf merger Mrk 709 has an interconnecting bridge of massive star clusters and an AGN in one component (Kimbrow et al. 2021). The dwarf galaxy NGC 4449 apparently has an even smaller galaxy falling in (Martínez-Delgado et al. 2012).

Stierwalt et al. (2015) compiled a catalog of 104 dwarf galaxy pairs and showed that the sSFR increases by a factor of about two when the galaxies get closer than 50 kpc. Pearson et al. (2016) studied the 10 closest of these pairs and suggested that the interaction disperses the disk gas, which then reaccretes later. Mergers are not obvious for most dIrrs: Higgs et al. (2021) found no evidence for merger structures in isolated local dwarfs considering galaxies closer to the Milky Way than 3 Mpc and more distant than 300 kpc from either the Milky Way or M31. Martin et al. (2021) suggested, based on a cosmological simulation, that less than 20% of dwarfs have morphological evidence for a merger at a redshift of $z = 3$, and less than 5% have merger evidence at $z = 1$; overall, mergers account for only 10% of the galaxy mass. Dwarf galaxy interactions are more common than mergers. Paudel et al. (2020) studied an interacting pair of dwarfs similar to the LMC–SMC pair near the spiral galaxy NGC 2998, which is like the Milky Way; they concluded that NGC 2998 is in a denser environment than the Milky Way and that the dwarfs near it are interacting primarily by tidal forces, whereas the LMC and SMC also show the effects of ram pressure stripping.

6.2. Accretion

Accretion onto dwarfs can be inferred in several ways, with direct evidence for gas flows being the most convincing. An example of this is in IC 10, which is a dwarf galaxy at a distance of 0.7 Mpc (Ashley et al. 2014, Namumba et al. 2019). **Figure 7a** from Ashley et al. (2014) shows an optical image with H_I from the Karl G. Jansky Very Large Array superimposed, and **Figure 7b** shows the H_I velocities with the near and far sides of the galaxy indicated along with the approaching and receding components of H_I. The nearside has gas receding from us, which means it is accreting onto the galaxy. A larger-scale view from the Green Bank Telescope is in **Figure 7c** from Ashley et al. (2014), which shows H_I to much larger distances following the same sense of motion, i.e., approaching the galaxy on both the near and far sides. These accretions apparently agitate the H_I in the disk also, as shown in **Figure 7d**, which plots the H_I velocity dispersion. The dispersion is low in the southern accretion stream but high in two places that could be stream impact sites. The accretion rate can be determined from the H_I mass and infall speed. For the northern filament, $M(\text{HI}) = 6 \times 10^5 M_{\odot}$, the relative speed is $\Delta v = 15 \text{ km s}^{-1}$, and the stream length is $L \sim 7 \text{ kpc}$, which combine to give an accretion rate of $M\Delta v/L = 0.001 M_{\odot} \text{ year}^{-1}$ and a time to finish of $\sim 0.6 \text{ Gyr}$. For the southern stream, $M(\text{HI}) = 10^7 M_{\odot}$, $\Delta v \sim 30 \text{ km s}^{-1}$, and $L \sim 7 \text{ kpc}$, giving an accretion rate of $\sim 0.04 M_{\odot} \text{ year}^{-1}$ and 0.2 Gyr to finish. The SFR of $0.04 M_{\odot} \text{ year}^{-1}$ (Ashley et al. 2014) is comparable with the accretion rate in the southern stream.

Analogous cases might be DDO 53 (Egorov et al. 2021) and Pisces A (Beale et al. 2020). The BCD galaxy NGC 2915 has high-speed clouds with different metallicities and a counter-rotating gas disk with respect to the stars, which is also evidence for accretion (Tang et al. 2022). In NGC 1569 (see outflow discussion in Section 2.2.2), Mühle et al. (2005) observed an H_I hole in the center of the wind and extended H_I halo structure suggesting accretion, as found by Stil & Israel (2002) and with deeper observations by Johnson et al. (2012). Not all dwarfs are accreting, though: NGC 6822 seems to have a net outflow (Fukagawa 2020). The MHONGOOSE program at the MeerKAT radio telescope is designed to detect gas accretion onto nearby galaxies using faint H_I emission (Sardone et al. 2021).

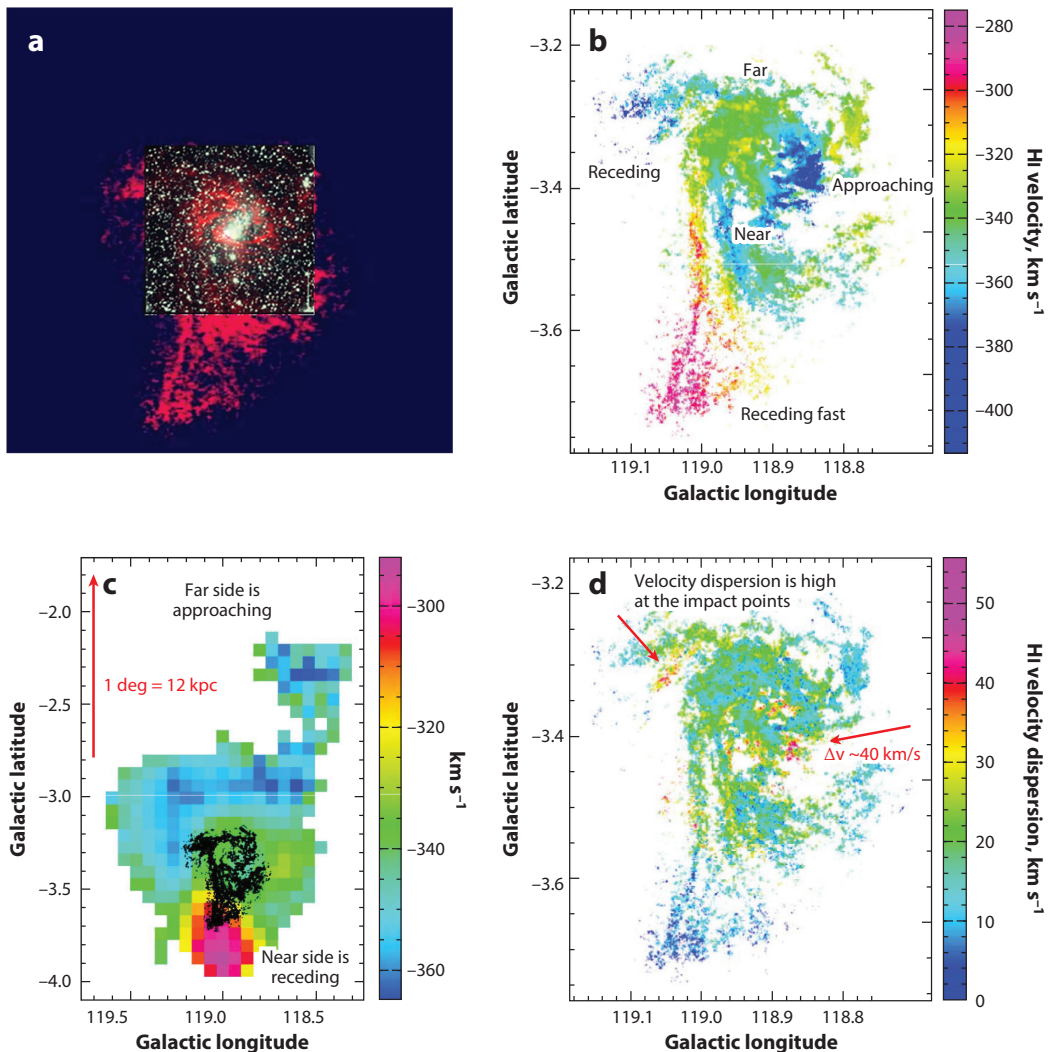


Figure 7

Local Group dIrr IC 10 with accretion. (a) Optical + JvLA-HI image (in red) with low HI contrast in the center of the panel, and the same HI image with higher contrast in the outer parts. (b) HI velocities with blue-shifted gas on the far side and red-shifted gas on the near side, indicating accretion (the near and far sides are determined from the winding of the spiral arms). (c) A larger view of HI from GBT with the same sense of accretion and the JvLA image in black. (d) HI velocity dispersion suggesting an increase in turbulent speed near the impact points. Figure adapted with permission from Ashley et al. (2014); copyright 2014 AAS. Abbreviations: GBT, Green Bank Telescope; JvLA, Jansky Very Large Array.

Accretion to dwarfs may also be observed as off-center star-formation hot spots, resembling “tadpoles” (van den Bergh et al. 1996), especially if the star-formation region has lower metallicity than the rest of the galaxy (Sánchez Almeida et al. 2018, Ju et al. 2022, del Valle-Espinosa et al. 2023). Three related studies of extremely metal-poor galaxies show metallicity drops at bright star-forming regions: Sánchez Almeida et al. (2013) observed 7 tadpoles and found 6 with metallicity drops, Sánchez Almeida et al. (2014) observed 7 and found 2 with metallicity drops, and Sánchez Almeida et al. (2015) observed 10 and found 9 with metallicity drops. CO observations of one of

these, Kiso 5639 (Elmegreen et al. 2016, 2018), revealed a $2.9 \times 10^7 M_{\odot}$ molecular cloud at the hot spot (assuming $\alpha_{\text{CO}} = 100 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ for 14% solar metallicity).

SUMMARY POINTS

1. Dwarf irregular (dIrr) galaxies are gas rich, low density, metal poor, and forming stars. As such, they are important stress tests for models of star formation.
2. Dwarf irregulars are thicker than spirals, and this affects star formation by making disk self-gravity weaker and 3D processes more important.
3. Stellar feedback is an important process in the evolution of dwarf galaxies because it can form large shells that may trigger star formation, dump metals into the circumgalactic medium (CGM), and increase the porosity of the gas, and because it can significantly modify the disk gravitational potential, causing stars to scatter around.
4. Molecular cloud structure in dwarf galaxies consists of tiny CO cores in thick photodissociation regions. However, the CO cores are similar to those in the Milky Way in terms of density, size–linewidth relation, and extinction. There could be substantial gas in dwarfs not traced by CO or H_I.
5. The dust-to-gas mass ratios (DGRs) are lower in dwarfs compared to spirals, the dust equilibrium temperatures are warmer, the dust grain sizes are smaller, and polycyclic aromatic hydrocarbons (PAHs) are nearly missing.
6. The low metallicities and DGRs in dIrrs affect the interstellar medium (ISM) and star formation by decreasing the mass fraction of cold molecular gas.

FUTURE ISSUES

1. Do we see evolutionary consequences of the large-scale dynamics predicted by dwarf galaxy simulations?
2. What drives turbulence in dwarf galaxies? New observations and tests are needed.
3. How are the self-gravitating H_I clouds that are precursors to star-forming molecular clouds formed? Radio interferometer surveys with high angular and spectral resolution may be able to address this.
4. Are dwarfs a significant source of reionization in the early Universe? High-angular-resolution, high-sensitivity far-infrared (FIR) observations may be able to answer this.
5. What are the consequences of the different structures of molecular clouds on the star-formation process and resulting stars? High-resolution and high-sensitivity radio interferometers are pushing maps of molecular clouds to lower metallicities, but at some metallicity will there be no CO in star-forming regions? How can we better trace CO-dark gas and what are its nature, amount, and distribution?
6. Where is star formation taking place within low-metallicity star-forming regions? Can it occur in dark H₂ or cold H_I without CO? In what component of the star-forming region are clumps of massive stars formed? How does this local, low-metallicity star

formation compare with star formation at high redshift? High-resolution, high-sensitivity FIR observations may answer these questions.

7. What is the reason for the dearth of PAH features in dwarf galaxies? How does the DGR behave at extremely low metallicities? How has the dust composition in dIrrs evolved over time?
8. What is the source of the excess submillimeter emission?
9. What is the nature of the CGM around dwarf irregulars, and how do the CGM and intergalactic medium (IGM) affect the evolution of these tiny galaxies? Spectra of background sources and ultradeep narrow-band imaging may address this.
10. How far does the gas disk extend in dIrrs and what role does highly extended gas play in the evolution of the galaxy? What fraction of dwarfs have evidence for cold-accretion from the IGM? Radio interferometers that can trace HI to very low column densities may be able to demonstrate how the IGM connects to the rest of the galaxy.

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